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Control of n2o-emissions by aeration

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Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Boiocchi, R., Sin, G., & Gernaey, K. V. (2017). Control of n2o-emissions by aeration. (Patent No. *WO2017207011*).

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(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
07 December 2017 (07.12.2017)

WIPO | PCT

(10) **International Publication Number**
WO 2017/207011 A1

(51) **International Patent Classification:**
C02F 3/00 (2006.01) *C02F 3/02* (2006.01)

(21) **International Application Number:**
PCT/DK2017/050186

(22) **International Filing Date:**
06 June 2017 (06.06.2017)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
PA201600331 03 June 2016 (03.06.2016) DK
PA201670400 06 June 2016 (06.06.2016) DK

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ,

(54) **Title:** CONTROL OF N_2O-EMISSIONS BY AERATION

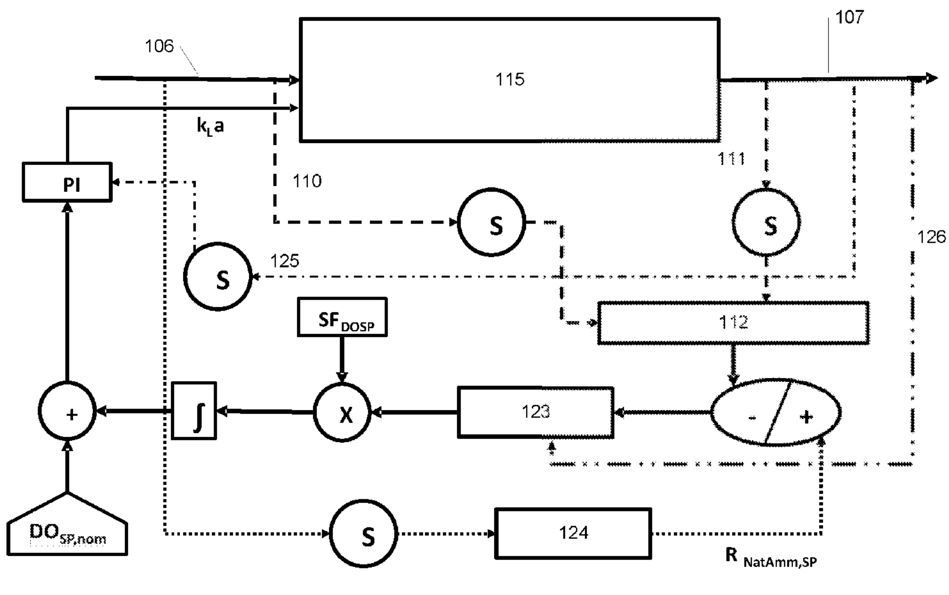

Fig. 6

(57) **Abstract:** Disclosed herein is a method and a system for controlling N_2O emission from a water-based solution containing nitrifying organisms, wherein an input variable for a controller is the ratio between NO_3^- produced and NH_4^+ oxidized as determined by measuring NO_3^- and NH_4^+ concentration both at the inlet and at the outlet of the aerated section containing the water-based solution with nitrifying organisms and a scaled output variable is obtained from the controller as a function of said ratio by a non-linear algorithm, so that the oxygen input and/or the aeration time is varied based on an integration of the deviations of said output variable.

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TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

Control of N_2O-emissions by aeration

The invention relates to a method for controlling the emission of N_2O during biological removal of NH_4^+ from a water-based solution such as waste water, drinking water or another aqueous solution having too high a content of NH_4^+. Biological removal means that microorganisms decompose unwanted substances. The invention also relates to a system comprising elements allowing reduced emission of N_2O during treatment of the water-based solution. In particular the invention relates to a control strategy providing control of the microbial turnover of NH_4^+ and resulting in a reduced emission of N_2O.

Background

Wastewater treatment plants are used for cleaning wastewater and in that process (among others) remove ammonium from the wastewater. Currently, the main focus when cleaning wastewater is to reduce – or preferably remove – the amount of potential harmful substances in the wastewater. Little focus has been on the gasses being released during such a cleaning process.

Nitrous oxide (N_2O) is well-known as an ozone-depleting substance and a harmful greenhouse gas with a global warming potential 300 times higher than carbon dioxide. Measurement campaigns at wastewater treatment plants (WWTPs) have revealed that a considerable amount of N_2O is normally emitted. Developing control strategies aiming at reducing the emissions of the greenhouse gasses, in particular N_2O, is therefore of interest.

During biological wastewater treatment processes, N_2O is found to be produced by two different microbial groups: ammonia-oxidizing bacteria (AOB) and heterotrophic bacteria (HB). In particular, AOB have shown their capability in using the produced NO_2^- instead of O_2 as electron acceptor for the oxidation of NH_4^+. The reduction of NO_2^- carries N_2O as end product.

Another possible pathway is the incomplete hydroxylamine oxidation by AOB. Intermediate compounds accumulated during this process can lead to N_2O. With regard to the role of HB, N_2O is produced as intermediate compound during the reduction of nitrogen oxides like NO_3^- and/or NO_2^- into N_2. If the reduction rate of N_2O into N_2 is slower than the reduction rate of N oxides into N_2O, an accumulation of N_2O can occur. The minimization of N_2O emissions can therefore be achieved by slowing down both the AOB-mediated N_2O-production processes and the net HB-mediated N_2O production process.

There is thus a need for a method for slowing down both the AOB-mediated N_2O-production processes and the net HB-mediated N_2O production process.

Description of the invention

Disclosed herein is a method for controlling N_2O emission from a water-based solution containing nitrifying organisms. The term water-based solution containing nitrifying organisms is meant to include wastewater treatment plants that employs a mixed culture of microorganism in particular Ammonium Oxidizing Bacteria (AOB) and Nitrite Oxidising Bacteria (NOB) in various reactor configurations such as granular or biofilm or suspended mixed culture systems or a hybrid system based on any combination of configuration employing nitrifying organisms. Systems that employ mixed culture of microorganisms that performs nitrification (AOB and NOB) – also referred to as microbial conversion of NH4-N – include as examples drinking water, process water, industrial wastewater treatment, soil treatment, are also included in the term water-based solution containing nitrifying organisms. Thus, examples of water-based solution containing nitrifying organisms include a wastewater solution with nitrifying organisms, a drinking water solution with nitrifying organisms, an industrial process water, an industrial wastewater solutions with nitrifying organisms, and similar.

The method comprises the step of providing an aerated section containing the water-based solution with nitrifying organisms. The aerated section may comprise one or more units in form of closed or open tanks or reactors.

By aerated is meant an “oxygen containing fluid”, which is provided by various aeration supply systems such as air, pure oxygen, surface aerators, bubble aeration and similar.

The aerated section is having an inlet for an oxygen containing fluid providing oxygen input to the aerated section for an aeration time, an inlet for leading the water-based solution into the aerated section, and an outlet for leading the water-based solution out of the aerated section.

The water-based solution with nitrifying organisms may flow through the aerated section at an aerated section flow rate.

The method further comprises the steps of:

- measuring the concentration of NH_4^+ ($[NH_4^+]_{IN}$) and NO_3^- ($[NO_3^-]_{IN}$) at the inlet of the aerated section or upstream of the aerated section, and
- measuring the concentration of NH_4^+ ($[NH_4^+]_{OUT}$) and NO_3^- ($[NO_3^-]_{OUT}$) at the outlet of the aerated section or downstream of the aerated section;

The method also comprises the step of providing a process or input variable R_{NatAmm} for a controller, the process or input variable corresponding to the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section.

In one or more embodiments, R_{NatAmm} is calculated by the equation:

$$R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}.$$

The method further comprises the steps of:

- obtaining a scaled output variable ($\Delta_S k_L a$, $k_L a$, $\Delta_U DO_{SP}$, AF,T_A) from the controller as a function of R_{NatAmm} by a non-linear algorithm, the value of the scaled output variable being between -1 and +1;
- obtaining a scaling factor ($SF_{\Delta SkLa}$, SF_{kLa}, $SF_{\Delta UDOSP}$, $SF_{AF,}$ SF_{TA}) determined by the chosen output variable
- multiplying the scaling factor with the scaled output variable in order to determine a deviation of the output variable, and
- providing a signal to an actuator varying the oxygen input to the aerated section based on an integration of the deviations of the output variable.

Alternatively, the method further comprises the steps of:

- obtaining a scaled output variable ($\Delta_S k_L a$, $k_L a$, $\Delta_U DO_{SP}$, AF,T_A) from the controller as a function of R_{NatAmm} by a non-linear algorithm, the value of the scaled output variable being between -1 and +1;
- obtaining a scaling factor ($SF_{\Delta SkLa}$, SF_{kLa}, $SF_{\Delta UDOSP}$, $SF_{AF,}$ SF_{TA}) determined by the chosen output variable
- multiplying the scaling factor with the scaled output variable in order to determine a deviation of the output variable, and
- providing a signal to an actuator varying the aeration time.

By varying the aeration time, i.e. the duration of the intermittent aeration, the time for the aerated periods and the time for unaerated periods in the aerated section is controlled. In intermittent aeration, there is a duration when the controller is active, i.e. switched on, and there is a duration when the controller is inactive, i.e. switched off. Therefore, these systems involve a cyclic operation where aerobic and anoxic phases alternate in each cycle by means of intermittent aeration. The total cycle time, T_C, thus includes an aerated time, T_A, where nitrification is allowed to proceed with NH_4^+ consumption and conversion to nitrite and/or nitrate; and the following anoxic phase, T_D, denitrification is allowed to proceed with consumption of NO_3^- and build-up of NH_4^+ . The aerated fraction, AF, defines the fraction of time within a cycle in which the reactor is aerated, AF= T_A/T_C..

Intermittent aeration, periodically aeration and aeration time is meant to refer to the same parameter.

In one or more embodiments, the oxygen input is kept constant and the aeration time is varied.

In one or more embodiments, the oxygen input is kept constant and the aeration time parameters such as T_C and or AF is varied.

In one or more embodiments, the aeration time is fixed and the oxygen input is varied.

Yet alternatively, the method further comprises the steps of:

- obtaining a scaled output variable ($\Delta_S k_L a$, $k_L a$, $\Delta_U DO_{SP}$ AF,T_A) from the controller as a function of R_{NatAmm} by a non-linear algorithm, the value of the scaled output variable being between -1 and +1;
- obtaining a scaling factor ($SF_{\Delta SkLa}$, SF_{kLa}, $SF_{\Delta UDOSP,}$ $SF_{TA,}$ SF_{AF}) determined by the chosen output variable
- multiplying the scaling factor with the scaled output variable in order to determine a deviation of the output variable, and
- providing a signal to an actuator varying the oxygen input to the aerated section, and/or the aeration time based on an integration of the deviations of the output variable.

Disclosed herein is also a system for treatment of a water-based solution containing nitrifying organisms.

The system comprises an aerated section having:

- an inlet for leading the water-based solution into the aerated section;
- an outlet for leading the water-based solution out of the aerated section,
- an inlet for an oxygen containing fluid providing oxygen input to the aerated section, and
- an outlet for gas emission;

The water-based solution with nitrifying organisms may flow through the aerated section at an aerated section flow rate.

The oxygen containing fluid may be provided by different aeration supply systems such as air, pure oxygen, surface aerators, bubble aeration, membrane aeration systems and similar.

The system also comprises:

- a first unit measuring an inlet value for NO_3^- concentration ($[NO_3^-]_{IN}$);
- a second unit measuring an outlet value for NO_3^- concentration ($[NO_3^-]_{OUT}$);
- a third unit measuring an inlet value for NH_4^+ concentration ($[NH_4^+]_{IN}$); and
- a fourth unit measuring an outlet value for NH_4^+ concentration ($[NH_4^+]_{OUT}$).

The system further comprises a non-linear controller unit adapted for:

- receiving the measured values for $[NO_3^-]_{IN}$, $[NO_3^-]_{OUT}$, $[NH_4^+]_{IN}$ and $[NH_4^+]_{OUT}$;
- calculating a process or output variable R_{NatAmm}, i.e. the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section, wherein R_{NatAmm} is e.g. calculated by using the equation: $R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}$;
- calculating an error variable $E_{RNatAmm}$, and
- providing an output variable for an actuator determining the supply of the oxygen containing fluid to the aerated section.

Alternatively, the system further comprises a non-linear controller unit adapted for:

- receiving the measured values for $[NO_3^-]_{IN}$, $[NO_3^-]_{OUT}$, $[NH_4^+]_{IN}$ and $[NH_4^+]_{OUT}$;

- calculating a process or output variable R_{NatAmm}, i.e. the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section, wherein R_{NatAmm} is e.g. calculated by using the equation: $R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}$;
- calculating an error variable $E_{RNatAmm}$, and
- providing an output variable for an actuator determining the aeration time.

Yet alternatively, the system further comprises a non-linear controller unit adapted for:

- receiving the measured values for $[NO_3^-]_{IN}$, $[NO_3^-]_{OUT}$, $[NH_4^+]_{IN}$ and $[NH_4^+]_{OUT}$;
- calculating a process or output variable R_{NatAmm}, i.e. the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section, wherein R_{NatAmm} is e.g. calculated by using the equation: $R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}$;
- calculating an error variable $E_{RNatAmm}$, and
- providing an output variable for an actuator determining 1) the supply of the oxygen containing fluid to the aerated section and 2) the aeration time.

By the method and system according to the above, it is possible to control the emission of N_2O during treatment of a water-based solution where the primary purpose is to remove NH_4^+ from the solution. This in particular useful in wastewater treatment plants where a reduction of the N_2O production can be reduced with at least 70-80 % without increasing the costs very much.

Brief description of the drawings

Figure 1 shows a layout of a Benchmark Simulation Model N°2 for Nitrous oxide.

Figure 2 is a block diagram for the implementation of a controller in the mainstream activated sludge unit.

Figures 3a-b show an embodiment of membership functions for RNatAmm (figure 3a) and ΔSkLa (figure 3b).

Figure 4 shows the dynamic and steady-state of influent TKN load simulated using the BSM2N model shown in figure 2.

Figures 5a-j show the dynamic results for both open-loop and closed-loop configurations of the N_2O emission (figure 5a, 5b, 5c), R_{NatAmm} (figure 5d, 5e, 5f), the oxygen mass transfer coefficient of the first aerobic tank (figure 5g), and the oxygen-to-nitrogen loading ratio (figure 5h, 5i, 5j).

Figure 6 shows a layout of another Benchmark Simulation Model N°2 for Nitrous oxide.

Figure 7a-b fuzzy-logic model used for $R_{NatAmm,SP}$ used in the layout of figure 6.

Figure 8a-c fuzzy-logic model used for set point for the oxygen control used in the layout of figure 6.

Figures 9a-c show the N_2O emission using a regular open-loop configuration and the fuzzy-logic controller of figure 6.

Figure 9d-f show the set point of dissolved oxygen and the actual dissolved oxygen.

Figure 10 is a table showing the N_2O emission both for TKN_{in} and TKN_{rem}, the TN and TKN rate, and the aeration cost.

Figure 11 shows the NH_4effluent concentration membership functions.

Figures 12a-b show 3D plots with the $\Delta_U DO_{SP}$ on the z axis and NH_4^+eff and $E_{RnatAmm}$ in the other two axes.

Description of preferred embodiments

In one or more embodiments, the system comprises a unit measuring dissolved oxygen concentration in the aerated section or at the outlet from the aerated section.

Since the conversion rate of organic nitrogen into nitrate is increased by an increased operating temperature, the optimal value for R_{NatAmm} is expected to increase in function of operating temperature. To take this into account, temperature adaptation of the set points for R_{NatAmm} may be included using a separate fuzzy-logic module, using the measured influent temperature as single input variable. Thus, in one or more embodiments, the system comprises a temperature transmitter positioned at the inlet to the aerated section or upstream of this inlet, and a second non-linear controller unit configured to receive a signal from the temperature transmitter.

In one or more embodiments, the system comprises an oxygen-transmitter registering the level of oxygen in the flow of water-based solution inside or at the outlet of the aerated section and a linear controller unit configured to receive a signal from the oxygen-transmitter.

For the development of a control strategy applied to biological wastewater processes, a fuzzy-logic approach may be the most suitable to be adopted. As a matter of fact, given their interactive nature and their high non-linearity, biological wastewater treatments can be more suitably controlled by non-linear controllers like fuzzy-logic controllers than by linear controllers like the Proportional Integrative Derivative (PID) ones.

Fuzzy-logic controllers (FLCs) present the additional possibility of incorporating expert knowledge about the processes to be controlled (R. Boiocchi *et al.,* J. Process Control. 30 (2015) 22–33). FLCs are also not affected by the capability of a mathematical model in describing realistically the processes to be controlled, since their design is independent from the model used. Furthermore, adopting a fuzzy-logic approach easily allows including the fuzziness associated with the control objectives, typically related to the wastewater treatment processes.

For these reasons, a FLC aiming at minimizing the N_2O emissions by balancing the activity of the different microbial groups is investigated further here.

In one or more embodiments, the non-linear algorithm is a fuzzy-logic model having membership functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “GOOD” when it is around 1, i.e. higher than 0.95 and preferably higher than 0.99 and lower than 1.3 and preferably lower than 1.2.

In one or more embodiments, the non-linear algorithm is a fuzzy-logic model having membership functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “LOW” when it is below 0.95, or below 0.99.

In one or more embodiments, the non-linear algorithm is a fuzzy-logic model having membership functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “HIGH” when it is higher than 1.3 or preferably 1.4.

If the input variable R_{NatAmm} is around 1, the process is not accumulating NO_2 and it should not be necessary to regulate the oxygen input to the aerated section. Even if the input variable R_{NatAmm} is slightly above 1, i.e. between 1.0 and 1.it should not be necessary to regulate. However, if R_{NatAmm} is below 0.99 it is considered necessary to increase the oxygen input to the aerated section and if R_{NatAmm} is above 1.2 it is necessary to reduce the oxygen input to the aerated section.

As an alternative to increasing or reducing the oxygen input, the duration of the aeration during intermittent (or periodically) aerated sections may be decreased or increased, respectively. By prolonging or shortening the time when the aeration is switched on in the aerated section, an effect similar to the effect obtained by controlling the oxygen input continuously can be observed.

By varying the aeration time, i.e. the duration of the intermittent aeration, the time for the aerated periods and the time for unaerated periods in the aerated section is controlled. In intermittent aeration, there is a duration when the controller is active, i.e. switched on, and there is a duration when the controller is inactive, i.e. switched off. Therefore, these systems involve a cyclic operation where aerobic and anoxic phases alternate in each cycle by means of intermittent aeration. The total cycle time, T_C, thus includes an aerated time, T_A, where nitrification is allowed to proceed with NH_4^+ consumption and conversion to nitrite and/or nitrate; and the following anoxic phase, T_D, denitrification is allowed to proceed with consumption of NO_3^- and build-up of NH_4^+ . The aerated fraction, AF, defines the fraction of time within a cycle in which the reactor is aerated, AF= T_A/T_C. Thus, a variation of the duration of the aeration (T_A or A_F) may be combined with the variation of the oxygen input rate (DeltaDOsp, DeltaKla or kla).

MATLAB/Simulink may be used as computer environment for the development of the fuzzy-logic control strategy. The model employed for testing its performance is the Benchmark Simulation Model N°2 for Nitrous oxide (BSM2N), developed by Boiocchi *et al.* (*Extending the benchmark simulation model no2 with processes for nitrous oxide production and side-stream nitrogen removal*, in: 12th Int. Symp. Process Syst. Eng.

25th Eur. Symp. Comput. Aided Process Eng., Elsevier, 2015: pp. 2477–2482). On this platform, dynamic simulations may be performed in order to evaluate the capability of the controller in reducing the N_2O emissions and its contextual effect on effluent quality and operational costs.

The BSM2N describes the physical and biochemical mainstream and side-stream processes occurring in a typical pre-denitrification WWTP. An overview of the configuration of the BSM2N is shown in Figure 1. As can be seen in the figure, the biological mainstream unit consists of two well-mixed anoxic tanks 101, 102 followed by three aerated tanks 103, 104 105. The biological processes occurring in the reactors 101, 102, 103, 104, 105 are described by an upgraded version of the Activated Sludge Model N°1 (ASM1) by Henze *et al.* (Water Res. 21 (1987) 505–515.), namely the Activated Sludge Model for Greenhouse gases N°1 (ASMG1) by Guo *et al.* (Bioprocess Biosyst. Eng. 37 (2014) 151–163).

Wastewater enters the tank system at an inlet position 106 and exits the tank system 101-105 at an outlet position 107. Sludge for disposal is led out at separate position 108.

The state variables of the ASMG1 are:

- oxygen (S_{O2});
- readily-biodegradable and slowly-biodegradable carbon (S_S and X_S, respectively);
- ammonium, nitrite, nitrate, dinitrogen, nitric and nitrous oxide nitrogen (S_{NHx}, S_{NO2}, S_{NO3}, S_{N2}, S_{NO} and S_{N2O}, respectively);
- soluble and particulate inerts (S_I and X_I, respectively);
- soluble and particulate organic nitrogen (S_{ND} and X_{ND}, respectively);
- alkalinity (S_{ALK}), and
- heterotrophic, ammonia-oxidizing and nitrite-oxidizing bacteria (X_{HB}, X_{AOB} and X_{NOB}, respectively).

The processes included in the ASMG1 are:

- aerobic growth of X_{HB};
- hydrolysis of X_S, hydrolysis of X_{ND};
- ammonification of S_{ND};
- aerobic growth of X_{AOB};

- aerobic growth of X_{NOB};
- anoxic growth of X_{HB} on S_{NO3}, on S_{NO2}, on S_{NO} and on S_{N2O};
- anoxic growth of X_{AOB} on S_{NO2} and on S_{NO}, and
- decay of X_{HB}, X_{AOB} and X_{NOB}.

The production of N_2O is modelled to be produced according to two pathways: 1) during HB denitrification and 2) during nitrite reduction (via nitric oxide) by AOB. The production of N_2O as a consequence of incomplete hydroxylamine (NH_2OH) oxidation by AOB is not included in the model, as a recently-developed model including the incomplete NH_2OH reveals that the amount of N_2O possibly produced during this process seems to be rather low compared to the amount of N_2O produced during AOB and HB denitrification (M. Pocquet *et al.*, Water Res. 88 (2015) 948–959.).

A fuzzy-logic inference system suitable for controlling the system of figure 1 consists of the following three main sequential operations:

1) Fuzzification, where numerical (crisp) inputs are converted into linguistic (fuzzy) inputs, according to predefined membership functions (MFs),
2) Fuzzy inference, where fuzzy outputs are deduced on the basis of the fuzzy inputs deduced in point 1), according to specified linguistic rules,
3) Defuzzification, where fuzzy outputs are converted into numerical (crisp) outputs according to predefined MFs and a chosen defuzzification method.

As can be deduced, the main parameters to be decided during the design of a fuzzy-logic controller are the MFs of input and output variables and the linguistic rules linking input to output variables.

The controller according to this invention is designed in such a way that it minimizes the production of N_2O by both AOB and HB. Heterotrophic denitrification can only occur under low oxygen conditions. The process can therefore occur in the anoxic zone in tanks 101 and 102 and at very poor oxygenation regimes in the aerobic zone in tanks 103, 104 and 105 (see figures 1 and 2).

The contribution on total N_2O by HB however is stronger in the aerobic zone 103, 104, 105 due to the higher mass transfer capability. In the anoxic zone 101, 102, the HB-produced N_2O stays in the liquid phase and thus is more likely to be reduced into N_2 rather than to strip.

With regard to the production of N_2O during AOB denitrification, it is well-established that low oxygen concentrations and/or high nitrite (NO_2^-) availability promote the use of NO_2^- itself by AOB as electron acceptor for the oxidation of ammonium (NH_4^+). Hence, for its minimization, in the aerobic zone, the oxygen has to be in a sufficiently high concentration to enhance the consumption of the AOB-produced NO_2^- by the coexisting microbial group, namely NOB. Enhancing the NOB activity by means of oxygen supply increase would contextually minimize the amount of N_2O produced by HB. Thus, the control of NOB activity can be beneficial for the reduction of the N_2O produced by both AOB and by HB.

For these reasons, monitoring the NOB activity over the one of AOB has been identified as a potential strategy for the minimization of the production of N_2O. The variable identified to be controlled at this purpose is the ratio between the nitrate produced by NOB and the ammonium consumed by AOB in the aerobic zone, expressed as R_{NatAmm} in Eqn. (1).

$$R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|} \qquad (1)$$

A value of R_{NatAmm} around 1 theoretically indicates that all the nitrite produced by AOB is subsequently consumed by NOB. If R_{NatAmm} is lower than 1, not all the AOB-produced NO_2^- is consumed by NOB. Thus NO_2^- starts accumulating in the system, which would in turn enhance AOB denitrification. This is a typical situation resulting from low oxygen availability.

On the other side, values of the R_{NatAmm} parameter significantly higher than 1 represent oxygen inhibition of heterotrophic denitrification, where an accumulation of HB-produced NO_2^- occurs. A too high oxygen supply would in part directly inhibit the HB-produced NO_2^- reduction and consume a larger amount of organic carbon needed by HB. In this scenario, the oxygen supply needs to be turned down to avoid that the accumulated NO_2^- to be reduced into N_2O.

In virtue of these considerations, the control strategy use measurements from the influent and effluent of the aerobic zone of NH_4^+ and NO_3^- for the calculation of R_{NatAmm}, namely the controlled variable.

The oxygen mass transfer coefficient (k_La) is used as a manipulated variable since changes in the oxygen availability forms the only available actuator that is able to induce the due shift on NOB activity. The fuzzy-logic controller described above is implemented in the mainstream aerobic zone as depicted in Figure 2. As can be seen, the concentration of NH_4^+ and NO_3^- before the wastewater enters the aerobic tanks 103, 104, 105 are measured at 110 and the concentration of NH_4^+ and NO_3^- after the wastewater exits the aerobic tanks 103, 104, 105 are measured at 111 and the values used for calculation R_{NatAmm} at a measuring unit 112.

The controller 113 will use the value of R_{NatAmm} as direct input variable and will deduce a scaled deviation of the oxygen mass transfer coefficient ($\Delta_S k_La$) as output variable. The latter will have a value between -1 and +1. The oxygen mass transfer coefficient ($\Delta_S k_La$) is then multiplied by a scaling factor (SF_{kLa}) at the unit 114 in order to obtain its physical dimension. The deviations of k_La are integrated in time and then added up to their respective nominal values.

In one or more embodiments, the membership functions for the input and output variables are defined as represented in Figures 3a-b. Table 1 shows the linguistic rules to enable deducing on the basis of the values of R_{NatAmm}, the variation of the k_La to be actuated on the three aerobic tanks.

Table 1: linguistic rules for a membership function

	IF	THEN
	R_{NatAmm}	**$\Delta_S k_La$**
1	LOW	POSITIVE
2	GOOD	ZERO
3	HIGH	NEGATIVE

R_{NatAmm} is considered to be “GOOD” when it is comprised within 0.99 and 1.2. The reason for allowing a value of R_{NatAmm} slightly higher than 1 is due to the fact that a fraction of the incoming organic nitrogen, after being hydrolysed and ammonified, is usually oxidized into NO_2^- and then NO_3^-. An amount of NO_3^- higher than the NH_4^+ (i.e.

R_{NatAmm}>1) consumed would therefore result. When R_{NatAmm} is in this range, no changes of k_La are designed to be actuated.

On the contrary, the maximal positive change of k_La (i.e. $\Delta_S k_L a$= 1) is decided to occur when R_{NatAmm} is equal or below 0.95, a scenario which would indicate that NOB need more oxygen for the conversion of NO_2^- into NO_3^-. When R_{NatAmm} is equal or higher than 1.4, inhibition of heterotrophic denitrification is considered to occur. In this case, the maximal negative change of k_La (i.e. $\Delta_S k_L a$=-1) is defined to be inferred by the control system.

A value for the k_La_{NOM} equal to 120 d^{-1} is assigned for the first two aerobic reactors 103, 104 and a value of 60 d^{-1} was used for last tank 105. A 240 d^{-1} value corresponding to the difference between the saturation limit of k_La (i.e. 360 d^{-1}) and the nominal value in the first two tanks (120 d^{-1}) is used as value for the scaling factor.

Simulations of a BSM2N open-loop and closed-loop configuration are performed with the aim of addressing the changes due to the implementation of the control strategy disclosed herein. In particular, the BSM2N is simulated with a 609-day long dynamic influent. The dynamic and the steady-state of the influent Total Kjeldahl Nitrogen (TKN) load for the last month are depicted in Figure 4.

Corresponding to the same period of time, Figures 5a-j show the dynamic results for both open-loop and closed-loop configurations of the N_2O emission factor in figure 5a calculated as percentage of N_2O emitted per unit of TKN in the influent, R_{NatAmm} in figure 5d, 5e, 5f, the oxygen mass transfer coefficient of the first aerobic tank 103 in figure 5g, and the oxygen-to-nitrogen loading ratio (RO) in figure 5h, 5i, 5j, calculated according to Eqn. (2) as the ratio between the oxygen supplied into the three aerobic tanks 103, 104, 105 and the TKN in the influent of the first anoxic tank 101.

$$RO = \frac{\sum_{i=1}^{3} V_i \cdot k_L a_i \cdot (S_{O,SAT} - S_{O,i})}{(S_{NH4,IN} + S_{ND,IN} + X_{ND,IN}) \cdot Q_{IN}} \qquad (2)$$

The present quantity indicates the typical aeration regime of the plant.

Following the BSM2 protocol for the benchmarking of control strategies from both the open-loop and closed-loop simulation results of the last 52 weeks, which allows a comparison more unbiased with regard to plant initial conditions and nominal value of k_La, the following average values are found:

- N_2O emission factors (N_2O_{ef}),
- total nitrogen removal efficiency (η_{TN}),
- R_{NatAmm},
- NO_2^- and NO_3^- effluent loads,
- Effluent limit violations in percentages of operating time for ammonium and total nitrogen (V_{NH4} and V_{TN}, respectively),
- Effluent Quality Index (EQI), calculated by taking into account the amount of the different pollutants in the effluent. The higher EQI is, the worst the effluent quality is,
- the average aeration energy (AAE), proportional to the oxygen mass transfer coefficients.

An overall evaluation of the impact of the controller implementation on the plant performance can thus be achieved and is summarized in Table 2.

Table 2: Open-loop and closed-loop plant performance evaluation.

	units	**OPEN LOOP**	**CLOSED LOOP**
$\mathbf{N_2O_{ef}}$	[% g N_2O-N_{EM}.g^{-1} TKN-N_{IN}]	0.4	0.26
$\mathbf{R_{NatAmm}}$	[g NO_3^--N.g^{-1} NH_4^+-N]	0.94	1.15
RO	[g $DO_{IN,AS}$.g^{-1} $TKN_{IN,AS}$]	4.7	5.3
$\mathbf{(NO_2^-)_{eff}}$	[kg NO_2^--N.d^{-1}]	2.3	0.36
$\mathbf{(NO_3^-)_{eff}}$	[kg NO_3^--N.d^{-1}]	167.6	269.1
$\mathbf{\eta_{TN}}$	[% g TN_{REM}.g^{-1} TN_{IN}]	70.8	60.7
$\mathbf{V_{NH4}}$	[% of operating time]	7.9	2.1
$\mathbf{V_{TN}}$	[% of operating time]	2.2	12.8
EQI	[kg poll.units.d^{-1}]	5386.8	5650.3
AAE	[kWh.d^{-1}]	4026.7	5242

As can be noted from table 2, the controller is able to reduce the average N_2O emitted by 35% by keeping the controlled variable, namely R_{NatAmm}, at a higher value. Thus NOB activity is enhanced and, consequently, a higher consumption of NO_2^- results, leading to lower NO_2^- load in the effluent.

The results of table 2 show that due to the higher NOB activity, the load of NO_3^- in the effluent is increased, which explains in turn the reduced TN removal efficiency (from 70.8% to 60.7%). The effluent quality index is therefore increased accordingly. Also the percentage of operating time in which TN violations (V_{TN}) are recorded is higher for the closed-loop configuration, although the percentage of operating time in which NH_4^+ violations (V_{NH}) occur is reduced due to the higher AOB resulting from the higher aeration. Since the controller has enhanced the NOB activity by increasing the amount of oxygen supplied, the average aeration costs have increased by approximately 30% compared to the open-loop case.

The results presented in figures 1-5 and in the table 1 and 2 show the capability of the controller in reducing significantly the average amount of N_2O emitted by speeding up the NOB activity, which prevents the AOB-produced NO_2^- from being reduced to N_2O. The results also suggest that reduction in the total N_2O emitted, which can be considered satisfactory, can be improved by further enhancing NOB activity.

Figure 6 shows an updated version of the model shown in figure 1, where the aerobic zone/section 115 may contain one or more open of closed aerobic tanks, e.g. the three aerobic tanks 103, 104, 105 as shown in figure 1.

The control system used in figure 6 adapts the aeration regime 115 in order to minimize the difference between a set-point of R_{NatAmm} ($R_{NatAmm,SP}$) and the actual R_{NatAmm}. The control concept is implemented using a feedback fuzzy logic control framework 123 similar in origin to the one used and described above for figures 1-5. However, compared to the previous implementation, the membership functions were finely tuned and significantly improved.

The set-point $R_{NatAmm,SP}$ changes automatically with the temperature of the influent wastewater at 106.

In one or more embodiments of the invention, the method comprises the step of measuring a temperature T of the water-based solution at one or more of the following locations:

- upstream of the inlet of the aerated section
- at the inlet of the aerated section

- inside the aerated section
- at the outlet of the aerated section
- downstream of the outlet from the aerated section.

The value is set to vary from 1.1 in cold seasons to 1.3 in warm seasons for a wastewater treatment plant in Europe/Scandinavia. This is included in a separate fuzzy-logic module 124. The control system manipulates the oxygen set point to be tracked by a Proportional Integrative (PI), which in turn manipulates the air supply (k_La).

In one or more embodiments of the invention, the method comprises the step of using the temperature T of the water-based solution for obtaining a set point ($R_{NatAmm,SP}$) for the variable R_{NatAmm}, wherein $R_{NatAmm,SP}$ is a function of T given by:

$$R_{NatAmm,SP} = \begin{cases} 1.1 \quad if\ T(t) \leq 10 \\ 0.02 \cdot T(t) + 0.9 \quad if\ 10 \leq T(t) \leq 20 \\ 1.3\ if\ T(t) \geq 20 \end{cases}$$

In order to optimally regulate the air supply, measurements of the following are needed:

- $[NO_3^-]$ and $[NH_4^+]$ 110 in to the aerobic zone 115;
- $[NO_3^-]$ and $[NH_4^+]$ 111 out of the aerobic zone 115;
- [DO] 125 of the aerobic zone 115;
- Temperature of the influent water 106 or the water in aerobic zone 115.

The fuzzy-module 124 used with the system in figure 6 is used to update the set point for $R_{NatAmm,SP}$ as a function of the temperature is shown in figures 7a-b, where figure 7a shows the input variable being the temperature and the output variable obtained therefrom in figure 7b.

The linguistic rules implemented in order to enable the module inferring the $R_{NatAmm,SP}$ on the basis of a measured temperature are shown in table 3.

Table 3. Linguistic rules implemented in order to enable the module inferring the $R_{NatAmm,SP}$

IF	THEN
"Temperature is LOW"	"$R_{NatAmm,SP}$ is LOW"

“Temperature is MEDIUM”	“$R_{NatAmm,SP}$ is MEDIUM”
“Temperature is HIGH”	“$R_{NatAmm,SP}$ is HIGH”

The fuzzy-logic module 123 used to infer the set point for the DO concentration is designed as shown in figure 8a, and the rules applying thereto in figure 8b. An alternative fuzzy-logic module 123 used to infer the set point for the DO concentration is designed as shown in figure 8c.

The input variable used in the model 123 is given as:

$$E_{RNatAmm} = R_{NatAmm,SP} - R_{NatAmm} \quad (3)$$

Thus, in one or more embodiments of the invention, the method comprises the step of calculating an error function defined by $E_{RNatAmm} = R_{NatAmm,SP} - R_{NatAmm}$.

In one or more embodiments, $E_{RNatAmm}$ is considered to be:

- “GOOD” when it is around 0, i.e. higher than -0.1 and lower than 0.1,
- “LOW” when it is below -0.2 and maybe up to -1, and
- “HIGH” when it is higher than 0.1 and up to 1.4.

Alternatively, in one or more embodiments, $E_{RNatAmm}$ is considered to be:

- “GOOD” when it is around 0, i.e. higher than -0.05 and lower than 0.05,
- “LOW” when it is below -0.4 and maybe up to -1, and
- “HIGH” when it is higher than 0.2 and up to 1.4.

Alternatively, in one or more embodiments, $E_{RNatAmm}$ is considered to be:

- “GOOD” when it is around 0, i.e. higher than -0.1 and lower than 0.1,
- “LOW” when it is below -0.1 and maybe up to -1, and
  - “HIGH” when it is higher than 0.1 and up to 1.4.

Alternatively, in one or more embodiments, $E_{RNatAmm}$ is considered to be:

- “GOOD” when it is around 0, i.e. higher than -0.05 and lower than 0.05,
- “LOW” when it is below -0.2 and maybe up to -1, and
- “HIGH” when it is higher than 0.2 and up to 1.4.

In one or more embodiments, NH_4^+eff is considered to be:

- "GOOD" when it is lower than 1.5, and
- "HIGH when it is higher than 2.

This is illustrated in figure 11. NH_4^+eff is normally obtained using the sensor 126 as shown in figure 6.

The output value is denoted $\Delta_U DO_{SP}$. The linguistic rules implemented in order to enable the control module 123 inferring the unitary variation of the oxygen set point on the basis of the difference between $R_{NatAmm,SP}$ and measured R_{NatAmm} are given in table 4.

In one or more embodiments, the linear controller receives a signal from the second non-linear controller ($\Delta_U DO_{SP}$), wherein the signal provides a set point for the measured level of oxygen (DOsp) in the flow of water-based solution leaving the aerated section.

Table 4. Linguistic rules used in the module 123.

IF	THEN
"$E_{RNatAmm}$ is LOW"	"$\Delta_U DO_{SP}$ is NEGATIVE"
"$E_{RNatAmm}$ is OK"	"$\Delta_U DO_{SP}$ is ZERO"
"$E_{RNatAmm}$ is HIGH"	"$\Delta_U DO_{SP}$ is POSITIVE"

In one or more embodiments of the invention, the method comprises the step of providing an output variable ($\Delta_U DO_{SP}$), wherein $\Delta_U DO_{SP}$ is scaled and provided as a set point to a linear feedback controller such as a P, PI or PID controller, wherein the linear feedback controller receives a process or input variable corresponding to a dissolved oxygen-content of the treated water-based solution and then provides a signal to an actuator determining an extent of aeration input to the aerated section.

For both the $R_{NatAmm,SP}$ fuzzy-logic module 124 and the R_{NatAmm} fuzzy-logic control module 123, the implication method chosen is the correlation-minimum, the aggregation method is the disjunction and the defuzzification method is the Center-of-Area.

The scaling factor is a scalar number which regulates only the speed of the controller. The scaling factor has to be of the same order of magnitude of the nominal value. A first attempt value for SF_{DOsp} is 1.

The system is tested on the BSM2 simulation model comparing control strategies for domestic wastewater treatment plants. The simulation results on the BSM2 using different mathematical models for N_2O production show a 70-80% N_2O emission reduction compared to the corresponding open-loop scenario. This is valid both in terms of N_2O emission per unit of influent Total Kjeldahl Nitrogen (TKN) and in terms of N_2O emission per unit of TKN removed. In figures 9a-c, the N_2O emission when using a regular open-loop configuration (OL) is compared to the closed-loop fuzzy-logic controller (CL). Figures 9d-f show the set point of dissolved oxygen and the actual dissolved oxygen.

The increment in aeration energy costs is minimal (2-6%). The control system is robust against sensor and actuator noises.

This is a large improvement of the results shown in figures 1-5 and proves the effect of the added robustness of the system achieved by: (I), finely tuning the membership functions for the input variable, and (II) including the temperature element, and (III) manipulating the DO_{SP} rather than the k_La in a cascade configuration which is in turn used by linear controller to calculate back the k_La .

Figure 10 is a table showing performance of the fuzzy logic controller with respect several performance metris: the percentage of N_2O emission relative to TKN_{in} and TKN_{rem} the percentage of TN removed and percentage of TKN removed, and the aeration cost (AEC) for the following four controller configurations:

(1) using the traditional well-known open-loop model of BSM2,
(2) the regulatory model, where the fuzzy logic controller acts directly on the k_la (figures 1-5),
(3) the cascade model, where the fuzzy logic controller acts on DOsp, which is then sent as input to the linear controller which acts on then k_la, and
(4) the sens and act model, which uses the cascade control configuration together with sensor and actuator models – adding sensor/actuator dynamics and noise as defined by BSM2.

The results are shown for three different mathematical models used for describing the biological processes occurring in a WWTP. Model A corresponds to a ASMG1 model, model B corresponds to a ASMG1 model with a first set of AOB production pathways, and model C corresponds to the ASMG1 model with another set of AOB production pathways.

As can be seen in the table in figure 10, the N_2O emission is greatly reduced with the method and system of the invention compared to the open-loop model. At the same time cost are comparable for the cascade model and the open-loop model.

The mathematics behind the fuzzy-logic modules used in this application can be described as follows:

The steps in the fuzzy logic model approach may follow the following scheme:

Step i) Calculation of R_{NatAmm} given by: $R_{NatAmm}(t) = \frac{NO_3^-|_{OUT}(t) - NO_3^-|_{IN}(t)}{NH_4^+|_{IN}(t) - NH_4^+|_{OUT}(t)}$

Step ii) Calculation of the set point for R_{NatAmm} as a function of the temperature T given by: $R_{NatAmm,SP} = \begin{cases} 1.1 & if\ T(t) \leq 10 \\ 0.02 \cdot T(t) + 0.9 & if\ 10 \leq T(t) \leq 20 \\ 1.3 & if\ T(t) \geq 20 \end{cases}$

Step iii) Calculation of fuzzy-logic controller input given by:
$E_{RNatAmm}(t) = R_{NatAmm,SP}(t) - R_{NatAmm}(t)$

Step iv) Calculation of the unitary variation of dissolved oxygen set point given by:

$$\Delta_U DO_{SP}(t) = \begin{cases} -1 & if\ E_{RNatAmm}(t) \leq -0.4 \\ 2.61 \cdot E_{RNatAmm}(t) + 0.079 & if\ -0.4 < E_{RNatAmm}(t) < -0.05 \\ 0 & if\ -0.05 \leq E_{RNatAmm}(t) \leq 0.05 \\ 6.36 \cdot E_{RNatAmm}(t) - 0.272 & if\ 0.05 < E_{RNatAmm}(t) < 0.2 \\ 1 & if\ E_{RNatAmm}(t) \geq 0.2 \end{cases}$$

Step v) Calculation of actual variation of the dissolved oxygen set point given by:
$\Delta DO_{SP}(t) = SF_{DOSP} \cdot \Delta_U DO_{SP}(t)$

Step vi) Calculation of the dissolved oxygen set point given by:
$DO_{SP}(t) = DO_{SP,nom} + \int \Delta DO_{SP}(t) \cdot dt$

Step vii) Calculation of the error between DOsp and measured oxygen concentration given by: $e(t) = DOsp(t) - DO(t)$

Step viii) Calculation of k_La given by: $k_L a(t) = K_p \cdot e(t) + K_I \cdot \int e(t) \cdot dt$

Alternatively the calculation of the unitary variation of dissolved oxygen set-point in step iv) is given by figures 12a-b, which are a 3D plot with the $\Delta_U DO_{SP}$ on the z axis and NH_4^+eff and $E_{RnatAmm}$ in the other two axes. It describes graphically the control law according to which the deltaUDOsp is derived on the basis of measured NH_4^+eff and $E_{RnatAmm}$. This is an alternative way of the mathematical expression of the control law, needed to be graphic because the inputs are two and not on as the case before where only $E_{RNatAmm}$ is used.

As shown in figure 6, the fuzzy-logic control module 123 may also receive input from the sensor 126 regarding the NH_4^+, effluent concentration at the outlet of the aerated section or downstream of the aerated section. While keeping R_{NatAmm} at its optimal value and thus reducing N_2O production, it is important to ensure a sustained ammonium conversion with the aim of respecting ammonium effluent limits. For this reason, the effluent ammonium concentration (NH_4^+, effluent) may be used as additional input to the control system to support taking the decision on the proper control action.

By this approach, one is able to directly take into account effluent ammonium concentration in the effluent. This adds on to the approaches focusing mainly on having a good ratio of R_{NatAmm}. In this approach, the flexibility is allowed to consider controlling effluent NH_4^+ quality in addition to having a good ratio of R_{NatAmm}.

The NH_4^+, effluent concentration may be integrated in an updated model, providing the linguistic rules used in the module 123 as shown in table 5.

Table 5. Linguistic rules used in the module 123

		$E_{RNatAmm}$		
		LOW	**GOOD**	**HIGH**
$(NH_4^+)_{eff}$	**GOOD**	**NEGATIVE**	**ZERO**	**POSITIVE**

	HIGH	**POSITIVE**	**POSITIVE**	**POSITIVE**

With regard to the manipulated variable used to achieve the control objective, either the oxygen supply, here represented by the oxygen mass transfer coefficient (k_La), or the oxygen concentration set point (DO_{SP}) of a Proportional Integral (PI) controller, may be adopted to regulate the oxygen input in the aerobic zone. The control structure in terms of disturbances ($\underline{d}$), states ($\underline{x}$), manipulated ($\underline{u}$) and controlled variables ($\underline{y}$) around an aerated zone may be summarized as:

$$\underline{d} = [NH^+_{4,in}, S_{S,in}, T_{in}, X_{S,in}, X_{P,in}, NO^-_{2,in}, NO^-_{3,in}, Q_{in}, NO_{in}, N_2O_{in}, N_{2,in}, X_{I,in}, S_{I,in}] \quad (4)$$

$$\underline{x} = [NH^+_4, S_S, T, X_S, X_P, NO^-_2, NO^-_3, NO, N_2O, N_2, X_I, S_I] \quad (5)$$

$$\underline{y} = [R_{NatAmm}, NH^+_{4,eff}] \quad (6)$$

$$\underline{u} = [k_La] \ or \ [DO_{SP}] \quad (7)$$

Based on the two manipulated variables shown in Eqn. (7), two generic control structures may be implemented in an aerobic section for the minimization of N_2O emissions.

The physical constraints on the controlled variables R_{NatAmm} and $[NH_4^+]_{eff}$ as shown in the figures may be expressed in Eqn. (8). As can be seen, both of them have a lower limit of zero. The upper limit for R_{NatAmm} is given by the sum of the unit, which is achieved when all the influent ammonium is converted into nitrate, and the ratio between the total amount of influent organic nitrogen ($N_{org,inAER}$) and the amount of influent ammonium consumed. As a matter of fact, as previously described, the organic nitrogen influent to the aerobic zone can be, under high oxygenation regimes, quickly hydrolysed and ammonified, oxidized into nitrite and finally converted into nitrate by NOB. Thus R_{NatAmm} can have values higher than unity. $TKN_{in,AER}$ is the Total Kjeldahl Nitrogen in the influent to the aerobic zone which is used to represent the maximal amount of effluent ammonium that could potentially be released. As a matter of fact, at rather poor oxygen levels, the influent ammonium is not consumed and, in addition, the influent organic nitrogen is hydrolysed and ammonified.

$$\begin{cases} 0 \le R_{NatAmm} \le \left(1 + \dfrac{N_{org,inAER}}{\Delta NH_4^+}\right) \\ 0 \le [NH_4^+]_{eff} \le TKN_{inAER} \end{cases} \quad (8)$$

All disturbances and state variables other than the oxygen concentrations in the aerobic zone can have theoretical values comprised between 0 and <+∞.

With regards to the effluent ammonium concentration ($[NH_4^+]$, eff), although a typical legal limit for effluent ammonium concentrations is 4 mg $N.L^{-1}$, in order to stay on the safe side, in an embodiment it may be decided that values higher than 2 mg $N.L^{-1}$ are considered the worst system operation requiring maximal control action. Optimal values for $[NH_4^+\text{-}N]_{eff}$ may be chosen to be equal or lower than 1.5 mg $N.L^{-1}$.

Eqns. (9-12) express the critical points for the vector of controlled variables identified for each system operation, optimal and worst, for different scenarios.

$$UB \text{ for } OPTIMAL\ SYSTEM\ OPERATION \Rightarrow \underline{y}_{UB,OPT} = [1.2 \quad 0] \quad (9)$$

$$LB \text{ for } OPTIMAL\ SYSTEM\ OPERATION \Rightarrow \begin{cases} y_{LB,OPT}^1 = [1.2 \quad 1.5] \\ y_{LB,OPT}^2 = [1.25 \quad 0] \\ y_{LB,OPT}^3 = [1.15 \quad 0] \\ y_{LB,OPT}^4 = [1.25 \quad 1.5] \\ y_{LB,OPT}^5 = [1.15 \quad 1.5] \end{cases} \quad (10)$$

$$UB \text{ for } WORST\ SYSTEM\ OPERATION \Rightarrow \begin{cases} y_{UB,WORST}^1 = [1.2 \quad 2] \\ y_{LB,OPT}^2 = [1.4 \quad 0] \\ y_{LB,OPT}^3 = [1 \quad 0] \\ y_{LB,OPT}^4 = [1.4 \quad 2] \\ y_{LB,OPT}^5 = [1 \quad 2] \end{cases} \quad (11)$$

$LB for\ WORST\ SYSTEM\ OPERATION$

$$\Rightarrow \begin{cases} y^1_{UB,WORST} = \left[1.2 \quad TKN_{in,AER}\right] \\ y^2_{UB,WORST} = \left[\left(1 + \frac{N_{org,inAER}}{\Delta NH_4^+}\right) \quad 1.5\right] \\ y^3_{UB,WORST} = [0 \quad 1.5] \\ y^4_{UB,WORST} = \left[\left(1 + \frac{N_{org,inAER}}{\Delta NH_4^+}\right) \quad TKN_{in,AER}\right] \\ y^5_{UB,WORST} = \left[0 \quad TKN_{in,AER}\right] \end{cases} \tag{12}$$

With regards to the shape of the membership functions for input and output variables, triangular and trapezoidal shapes may be chosen for the sake of simplicity.

The last step consists in the assignment of the degree of membership to fuzzy sets previously identified for each numerical value of R_{NatAmm} and $[NH_4^+\text{-}N_{eff}]$. A degree of membership to the identified fuzzy sets equal to 1 may be assigned to the critical points defined in subsection 2.2 as expressed in Eqns. (13-16). A degree of membership equal to 0 to the other fuzzy sets may be assigned to the same critical points.

$$UB \text{ for } OPTIMAL\ SYSTEM\ OPERATION \Rightarrow \begin{cases} (R_{NatAmm})_{GOOD} = 1.2 \\ \left(NH^+_{4,eff}\right)_{GOOD} = 0 \end{cases} \tag{13}$$

$$LB \text{ for } OPTIMAL\ SYSTEM\ OPERATION \Rightarrow \begin{cases} (R_{NatAmm})_{GOOD} = 1.15\ and\ 1.25 \\ \left(NH^+_{4,eff}\right)_{GOOD} = 1.5 \end{cases} \tag{14}$$

$$UB \text{ for } WORST\ SYSTEM\ OPERATION \Rightarrow \begin{cases} (R_{NatAmm})_{LOW} = 1 \\ (R_{NatAmm})_{HIGH} = 1.4 \\ \left(NH^+_{4,eff}\right)_{HIGH} = 2 \end{cases} \tag{15}$$

$$LB \text{ for } WORST\ SYSTEM\ OPERATION \Rightarrow \begin{cases} (R_{NatAmm})_{LOW} = 0 \\ (R_{NatAmm})_{HIGH} = \left(1 + \frac{N_{org,inAER}}{\Delta NH_4^+}\right) \\ \left(NH^+_{4,eff}\right)_{HIGH} = TKN_{in,AER} \end{cases} \tag{16}$$

Abbreviation list

WWTP	Wastewater treatment plants
AOB	Ammonia-oxidizing bacteria
NOB	Nitrite-oxidizing bacteria
HB	Heterotrophic bacteria
FLC	Fuzzy logic controller
BSM2N	Benchmark Simulation Model no 2 for Nitrous oxide
ANOX	Anoxic tank
AER	Aerobic tank
ASMG1	Activated Sludge Model for Greenhouse gases no1
R_{NatAmm}	Ratio between NO_3^- produced and NH_4^+ oxidized
$R_{NatAmm,SP}$	Set point of R_{NatAmm}
MF	Membership functions
k_La	Oxygen mass transfer coefficient
$\Delta_S k_La$	Unitary deviation of k_La
DO_{SP}	Set point of dissolved oxygen
$\Delta_S DO_{SP}$	Unitary deviation of DO_{SP}
$SFDO_{SP}$	Scaling factor for DO_{SP}
k_LaNOM	Nominal value for k_La
SFk_La	Scaling factor for k_La
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
η_{TN}	TN removal efficiency
EQI	Effluent Quality Index

Claims

1. Method for controlling N_2O emission from a water-based solution containing nitrifying organisms, the method comprising the steps of:
   - providing an aerated section containing the water-based solution with nitrifying organisms, the aerated section having:
     - an inlet for an oxygen containing fluid providing oxygen input to the aerated section for an aeration time;
     - an inlet for leading the water-based solution into the aerated section, and
     - an outlet for leading the water-based solution out of the aerated section;
   - measuring the concentration of NH_4^+ ($[NH_4^+]_{IN}$) and NO_3^- ($[NO_3^-]_{IN}$) at the inlet of the aerated section or upstream of the aerated section;
   - measuring the concentration of NH_4^+ ($[NH_4^+]_{OUT}$) and NO_3^- ($[NO_3^-]_{OUT}$) at the outlet of the aerated section or downstream of the aerated section;
   - providing a process or input variable R_{NatAmm} for a controller, the process or input variable corresponding to the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section, wherein R_{NatAmm} is e.g. calculated by the equation: $R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}$,
   - obtaining a scaled output variable ($\Delta_S k_L a$, $k_L a$, $\Delta_U DO_{SP}$, AF,T_A) from the controller as a function of R_{NatAmm} by a non-linear algorithm, the value of the scaled output variable being between -1 and +1;
   - obtaining a scaling factor ($SF_{\Delta SkLa}$, SF_{kLa}, $SF_{\Delta UDOSP}$, $SF_{AF,}$ SF_{TA}) determined by the chosen output variable;
   - multiplying the scaling factor with the scaled output variable in order to determine a deviation of the output variable, and
   - providing a signal to an actuator varying the oxygen input to the aerated section, and/or the aeration time based on an integration of the deviations of the output variable.

2. Method according to claim 1, wherein R_{NatAmm} is calculated by the equation: $R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}$.

3. Method according to any preceding claim, wherein the oxygen input is kept constant and the aeration time varied.

4. Method according to the claims 1-2, wherein the aeration time is fixed and the oxygen input is varied.

5. Method according to any preceding claim, wherein the non-linear algorithm is a fuzzy-logic model having memberships functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “GOOD” when it is around 1, i.e. higher than 0.95 and preferably higher than 0.99 and lower than 1.3 and preferably lower than 1.2.

6. Method according to any preceding claim, wherein the non-linear algorithm is a fuzzy-logic model having memberships functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “LOW” when it is below 0.95, or below 0.99.

7. Method according to any preceding claim, wherein the non-linear algorithm is a fuzzy-logic model having memberships functions for the process or input variables and the output variables, wherein the input variable R_{NatAmm} is considered to be “HIGH” when it is higher than 1.3 or preferably 1.4.

8. Method according to any preceding claim further comprising the step of measuring a temperature T of the water-based solution at one or more of the following locations:
   - upstream of the inlet of the aerated section
   - at the inlet of the aerated section
   - inside the aerated section
   - at the outlet of the aerated section
   - downstream of the outlet from the aerated section.

9. Method according to claim 8 comprising the step of using the temperature T of the water-based solution for obtaining a set point ($R_{NatAmm,SP}$) for the variable R_{NatAmm}, wherein $R_{NatAmm,SP}$ is a function of T given by

$$R_{NatAmm,SP} = \begin{cases} 1.1 \quad if\ T(t) \leq 10 \\ 0.02 \cdot T(t) + 0.9 \quad if\ 10 \leq T(t) \leq 20 \\ 1.3\ if\ T(t) \geq 20 \end{cases}$$

10. Method according to claim 9 comprising the step of calculating an error function defined by $E_{RNatAmm} = R_{NatAmm,SP} - R_{NatAmm.}$

11. Method according to claim 10, wherein $E_{RNatAmm}$ is considered to be:
    - “GOOD” when it is around 0, i.e. higher than -0.1 and lower than 0.1,
    - “LOW” when it is below -0.2 and maybe up to -1, and
    - “HIGH” when it is higher than 0.1 and up to 1.4.

12. Method according to any of the claims 11 further comprising the step of providing an output variable ($\Delta_U DO_{SP}$), wherein $\Delta_U DO_{SP}$ is scaled and provided as a set point to a linear feedback controller such as a P, PI or PID controller, wherein the linear feedback controller receives a process or input variable corresponding to a dissolved oxygen-content of the treated water-based solution and then provides a signal to an actuator determining an extent of aeration input to the aerated section.

13. System for treatment of a water-based solution containing nitrifying organisms, the system comprising:
    - an aerated section having:
        - an inlet for leading the water-based solution into the aerated section;
        - an outlet for leading the water-based solution out of the aerated section,
        - an inlet for an oxygen containing fluid providing oxygen input to the aerated section for an aeration time, and
        - an outlet for gas emission;
    - a first unit measuring an inlet value for NO_3^- concentration ($[NO_3^-]_{IN}$);
    - a second unit measuring an outlet value for NO_3^- concentration ($[NO_3^-]_{OUT}$);
    - a third unit measuring an inlet value for NH_4^+ concentration ($[NH_4^+]_{IN}$); and
    - a fourth unit measuring an outlet value for NH_4^+ concentration ($[NH_4^+]_{OUT}$),
    - a non-linear controller unit adapted for:
        - receiving the measured values for $[NO_3^-]_{IN}$, $[NO_3^-]_{OUT}$, $[NH_4^+]_{IN}$ and $[NH_4^+]_{OUT}$;
        - calculating a process or input variable R_{NatAmm}, i.e. the ratio between NO_3^- produced and NH_4^+ oxidized inside the aerated section, wherein R_{NatAmm} is e.g. calculated by using the equation:

$$R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|};$$

- calculating an error variable $E_{RNatAmm}$, and
- providing an output variable for an actuator determining:
  a) the supply of the oxygen containing fluid to the aerated section, and/or
  b) the aerating time.

14. A system according to claim 13, wherein R_{NatAmm} is calculated by the equation:

$$R_{NatAmm} = \frac{|(NO_3^-)_{IN} - (NO_3^-)_{OUT}|}{|(NH_4^+)_{IN} - (NH_4^+)_{OUT}|}.$$

15. A system according to claim 13 or 14 further comprising a unit measuring dissolved oxygen concentration in the aerated section or at the outlet from the aerated section.

16. A system according to any of the claims 13-15, wherein the system further comprises a temperature transmitter positioned at the inlet to the aerated section or upstream of this inlet, and a second non-linear controller unit configured to receive a signal from the temperature transmitter.

17. A system according to claim 16, wherein the temperature is used to calculate a setpoint variable $R_{NatAmm,SP}$ according to claim 9.

18. A system according to any of the previous claims 13-17, wherein $E_{RNatAmm} = R_{NatAmm,SP} - R_{NatAmm}$.

19. A system according to any of the previous claims 13-18, wherein the system further comprises an oxygen-transmitter registering the level of oxygen in the flow of water-based solution inside or at the outlet of the aerated section and a linear controller unit configured to receive a signal from the oxygen-transmitter.

20. A system according to claim 19, wherein the linear controller receives a signal from the second non-linear controller ($\Delta_U DO_{SP}$), wherein the signal provides a set point for the measured level of oxygen (DOsp) in the flow of water-based solution leaving the aerated section.

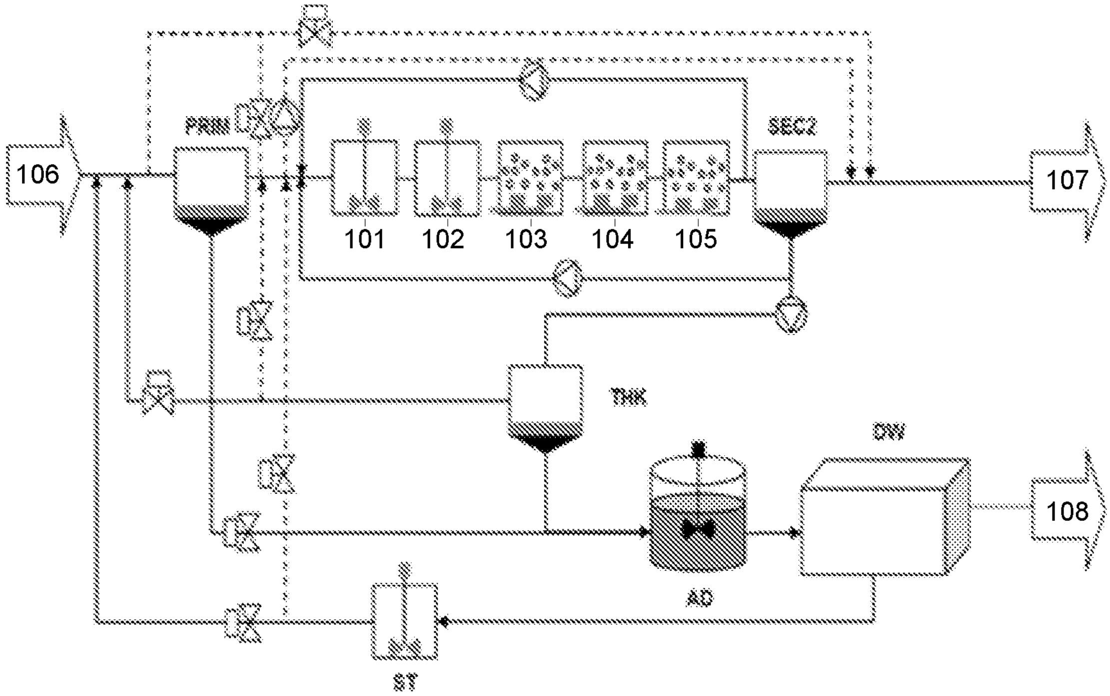
106
PRIM
101
102
103
104
105
SEC2
107
THK
DW
108
AD
ST

Fig. 1

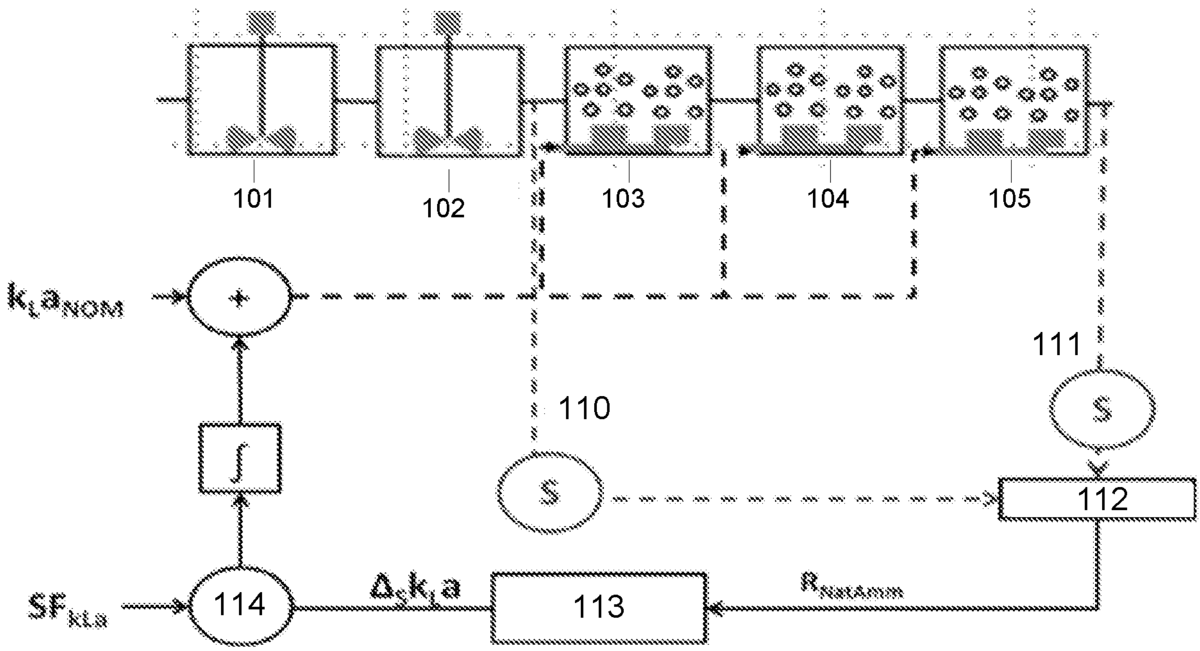
101
102
103
104
105
k_La_{NOM}
+
∫
111
110
S
S
112
SF_{kLa}
114
$\Delta_S k_L a$
113
R_{NatAmm}

Fig. 2

2/17

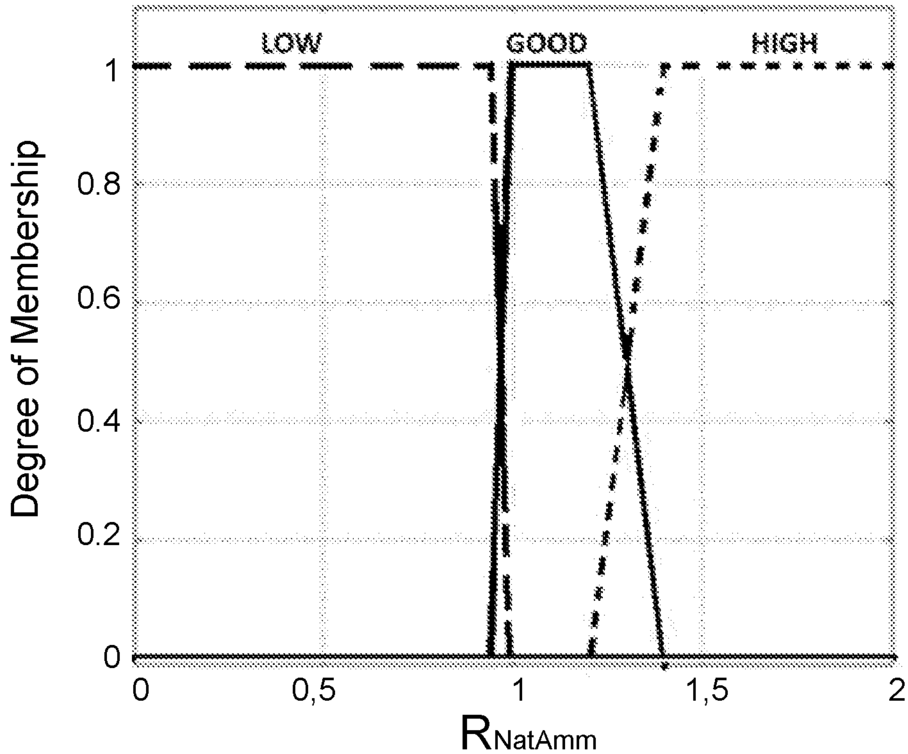

Fig. 3a

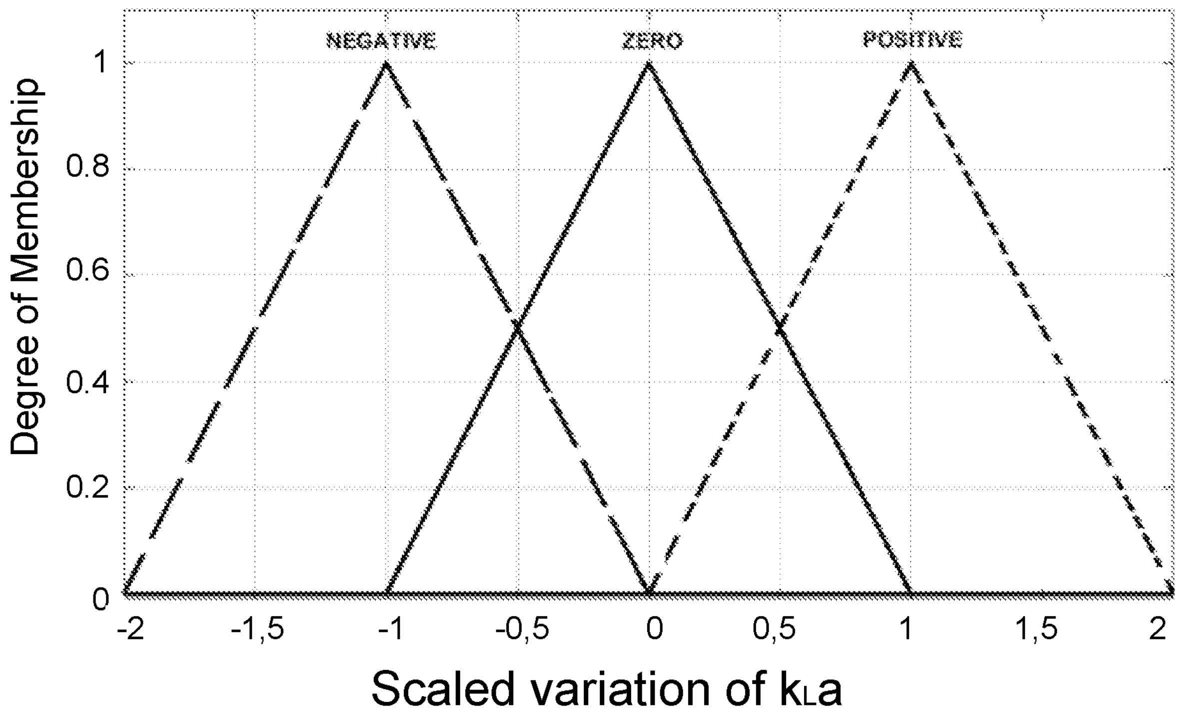

Fig. 3b

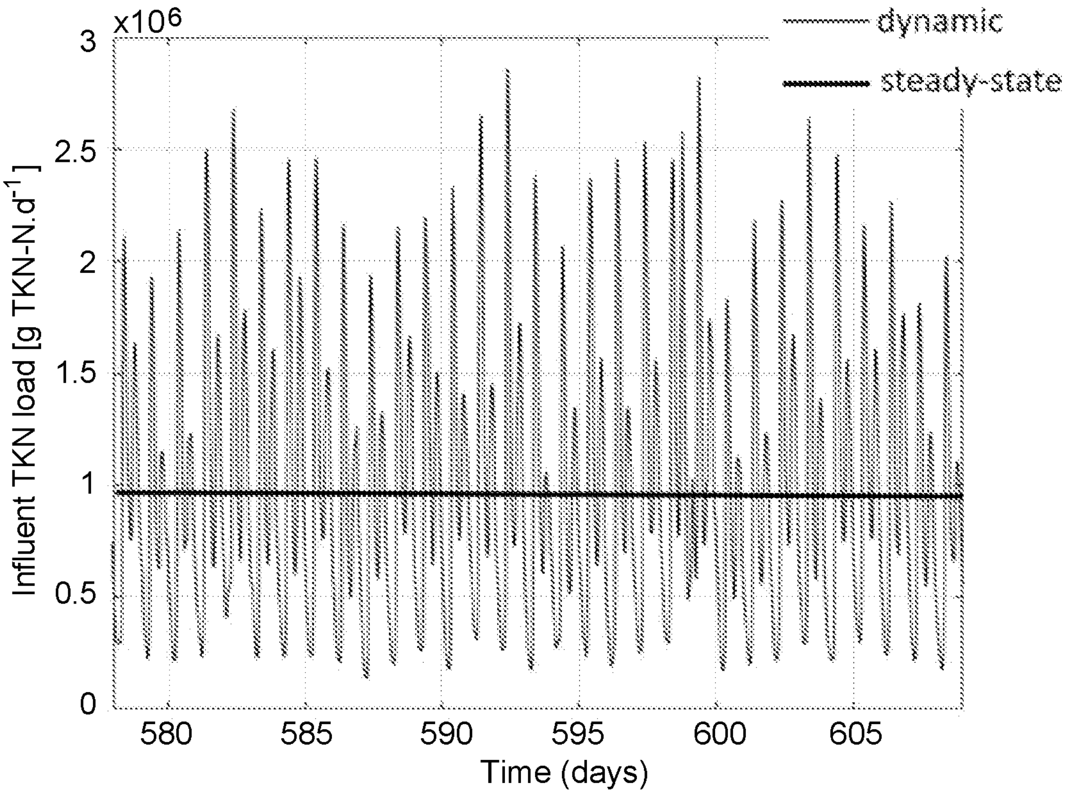
x10^6
dynamic
steady-state
Influent TKN load [g TKN-N.d^-1]
Time (days)
0
0.5
1
1.5
2
2.5
3
580
585
590
595
600
605

Fig. 4

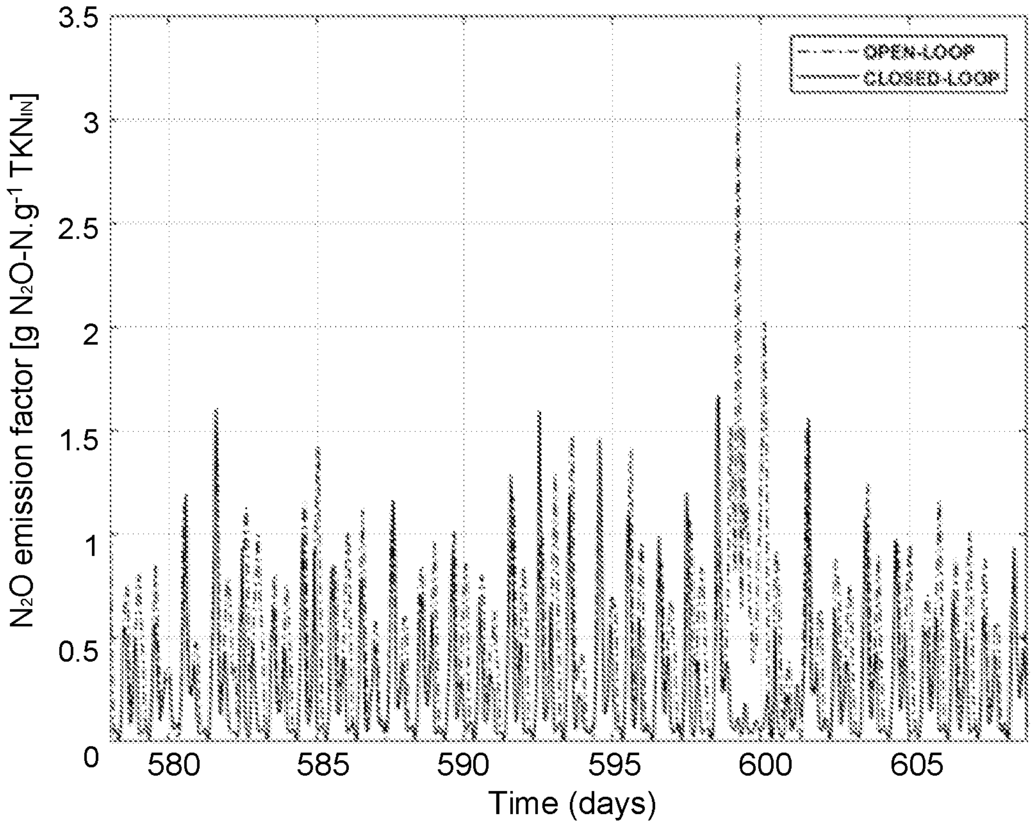
OPEN-LOOP
CLOSED-LOOP
N2O emission factor [g N2O-N.g^-1 TKN_IN]
Time (days)
0
0.5
1
1.5
2
2.5
3
3.5
580
585
590
595
600
605

Fig. 5a

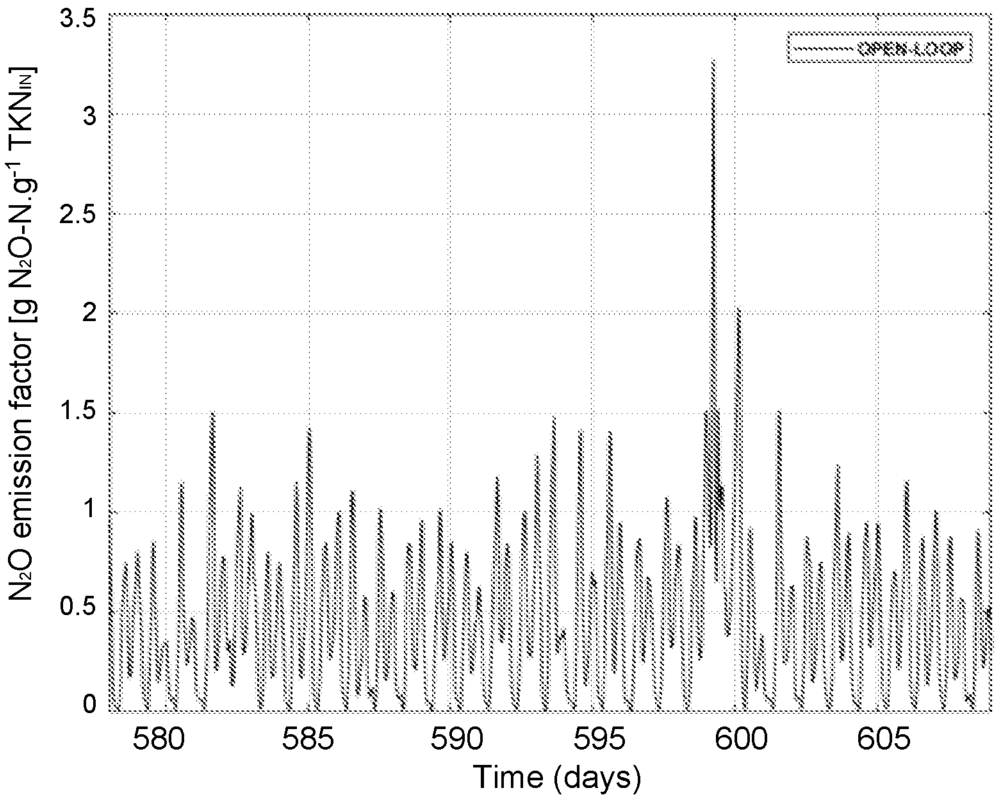
OPEN-LOOP
N2O emission factor [g N2O-N.g-1 TKNIN]
3.5
3
2.5
2
1.5
1
0.5
0
580
585
590
595
600
605
Time (days)

Fig. 5b

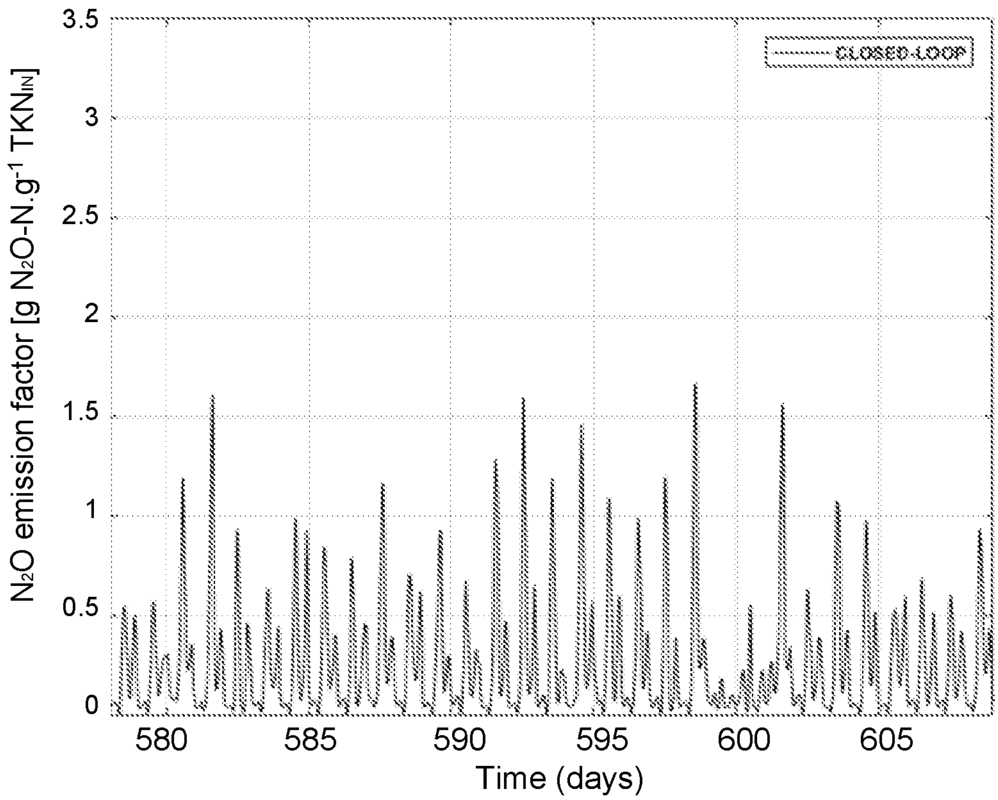
CLOSED-LOOP
N2O emission factor [g N2O-N.g-1 TKNIN]
3.5
3
2.5
2
1.5
1
0.5
0
580
585
590
595
600
605
Time (days)

Fig. 5c

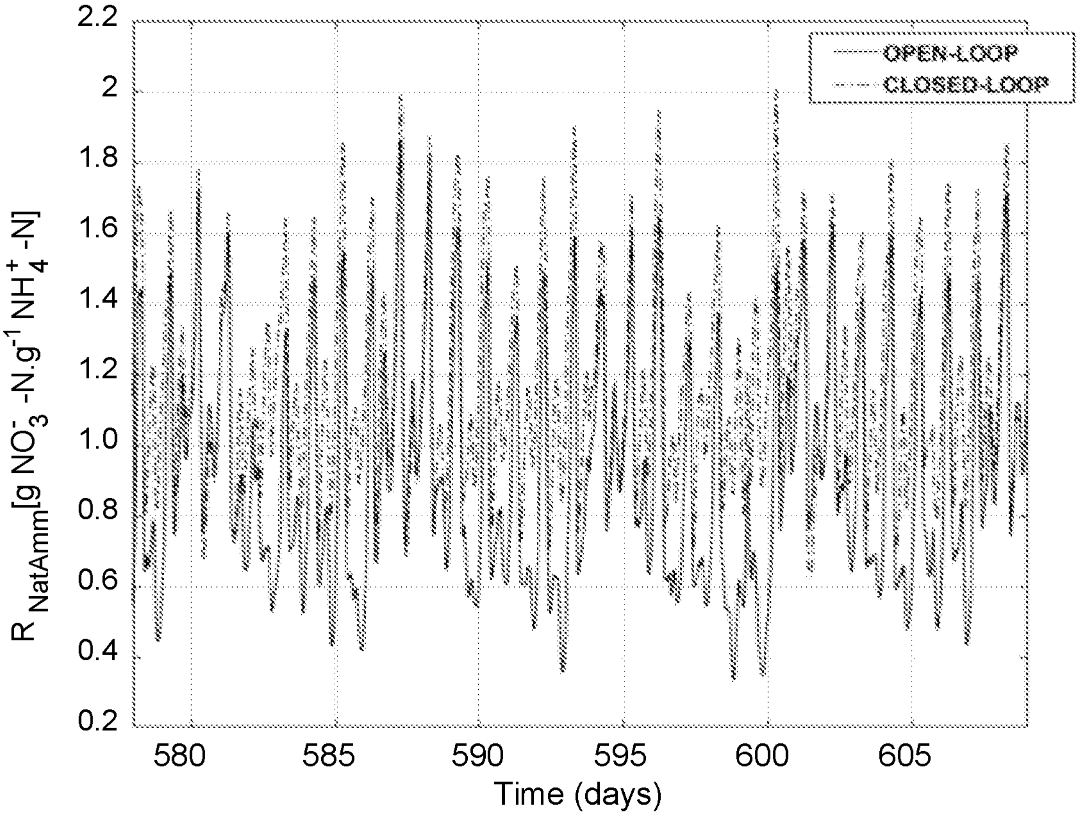
2.2
2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$R_{NatAmm}[g\ NO_3^- -N.g^{-1}\ NH_4^+ -N]$
OPEN-LOOP
CLOSED-LOOP
580
585
590
595
600
605
Time (days)

Fig. 5d

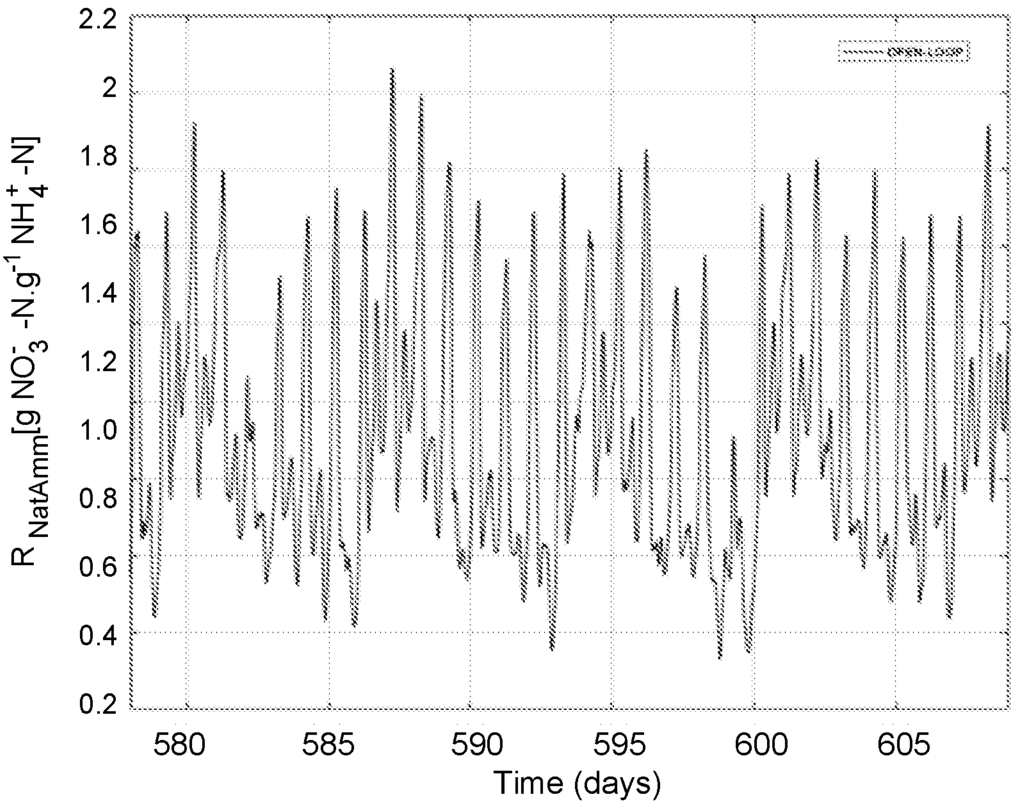
2.2
2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
$R_{NatAmm}[g\ NO_3^- -N.g^{-1}\ NH_4^+ -N]$
OPEN-LOOP
580
585
590
595
600
605
Time (days)

Fig. 5e

6/17

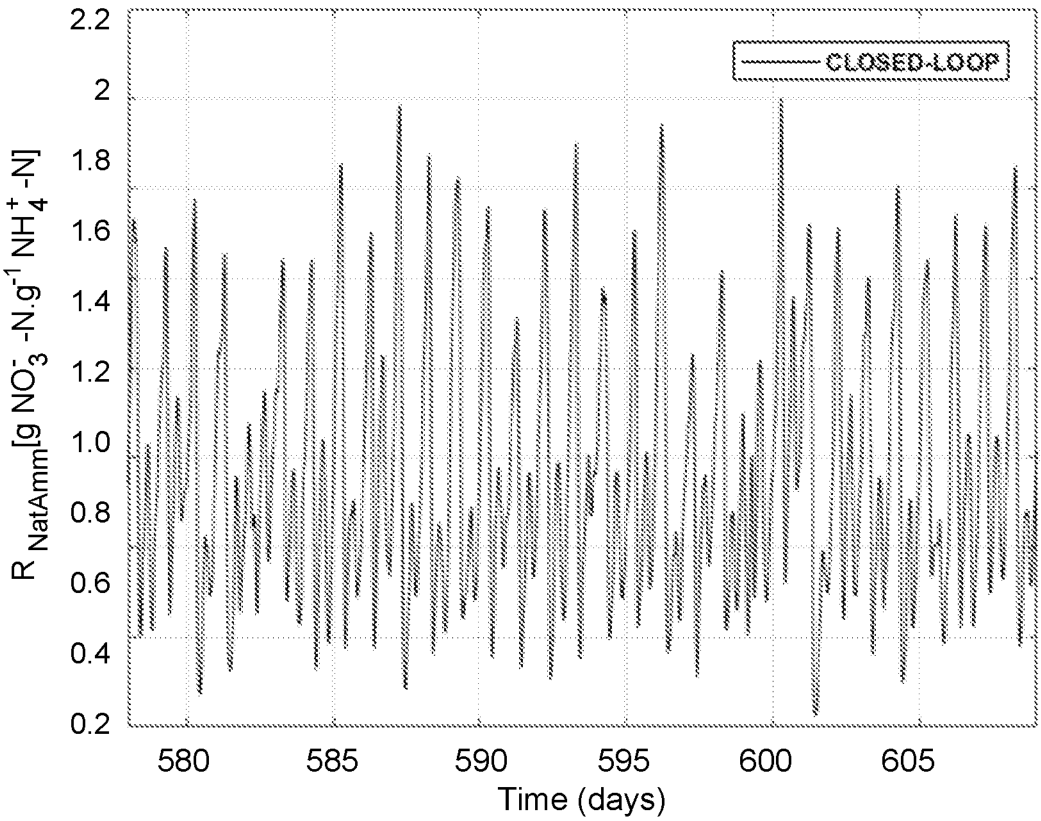

Fig. 5f

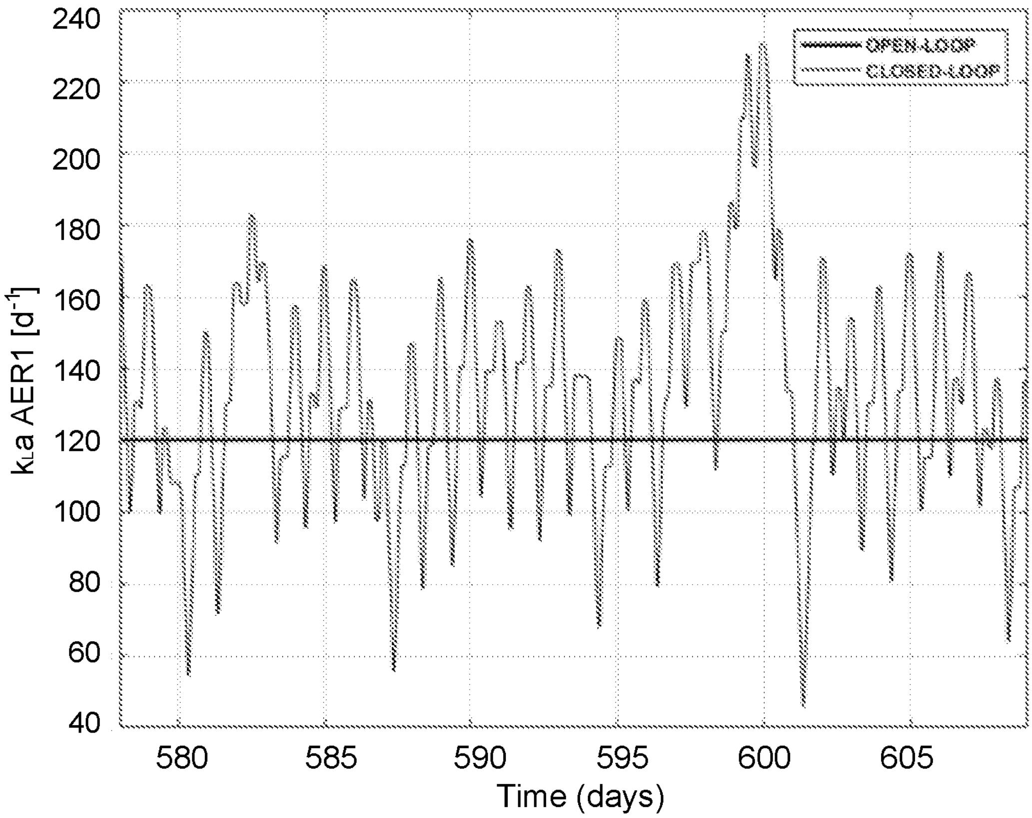

Fig. 5g

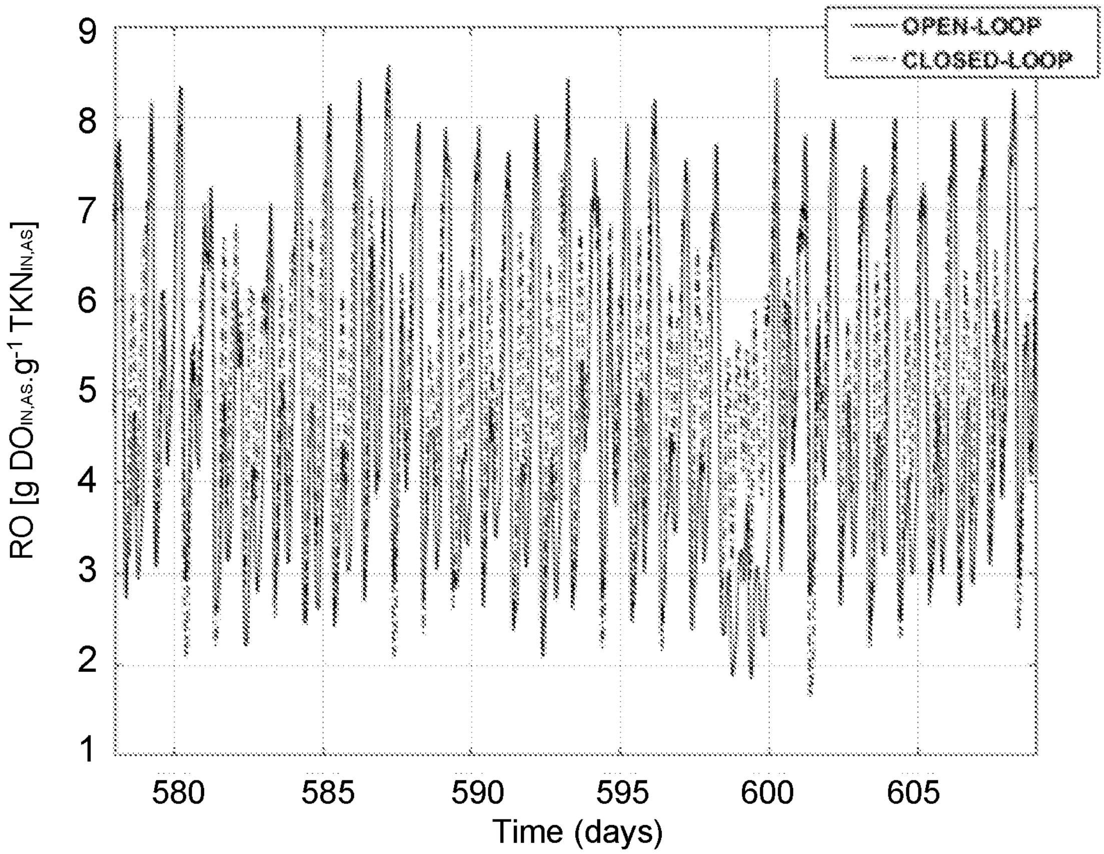
OPEN-LOOP
CLOSED-LOOP
RO [g DO$_{IN,AS}$.g^{-1} TKN$_{IN,AS}$]
9
8
7
6
5
4
3
2
1
580
585
590
595
600
605
Time (days)

Fig. 5h

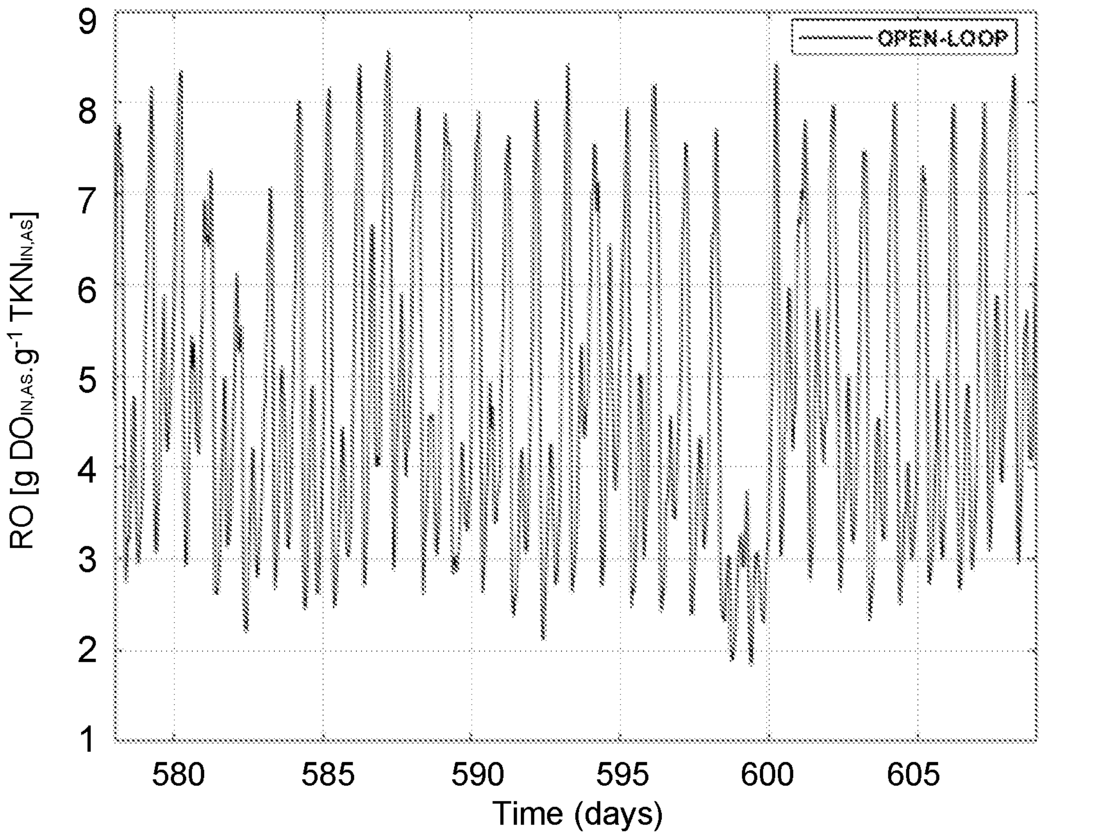
OPEN-LOOP
RO [g DO$_{IN,AS}$.g^{-1} TKN$_{IN,AS}$]
9
8
7
6
5
4
3
2
1
580
585
590
595
600
605
Time (days)

Fig. 5i

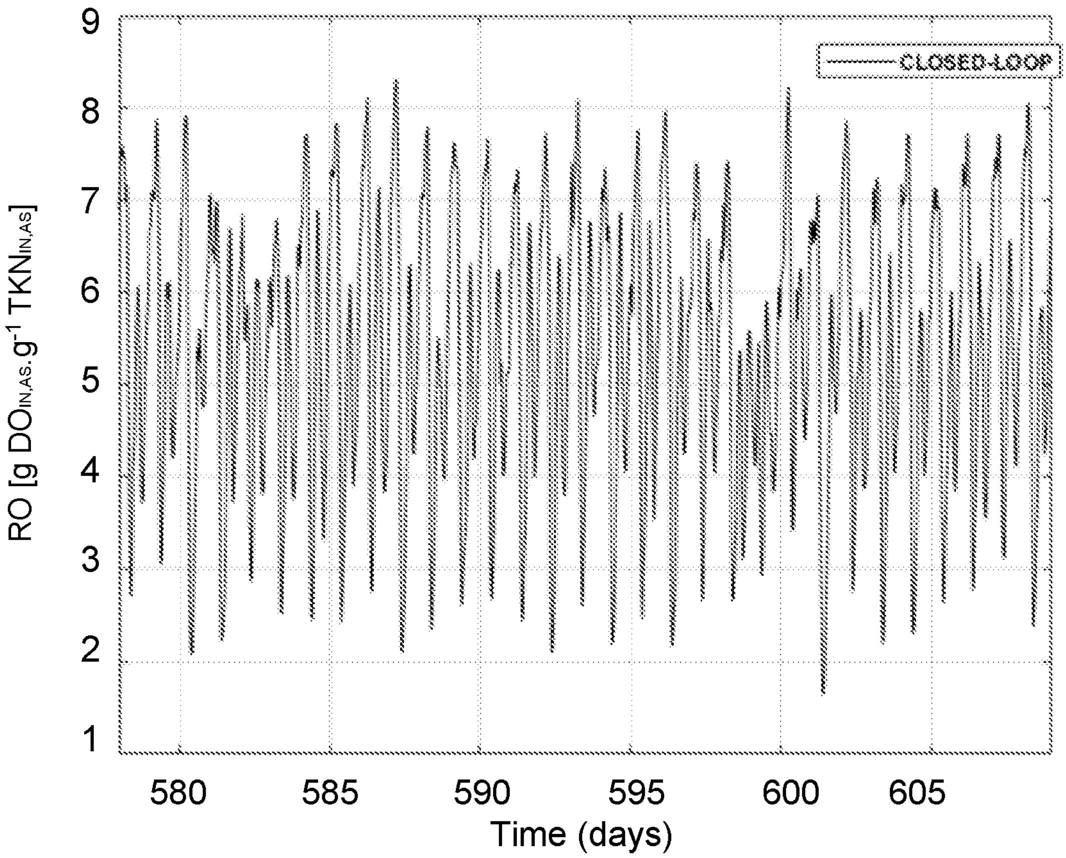
CLOSED-LOOP
RO [g $DO_{IN,AS}$.g^{-1} $TKN_{IN,AS}$]
9
8
7
6
5
4
3
2
1
580
585
590
595
600
605
Time (days)

Fig. 5j

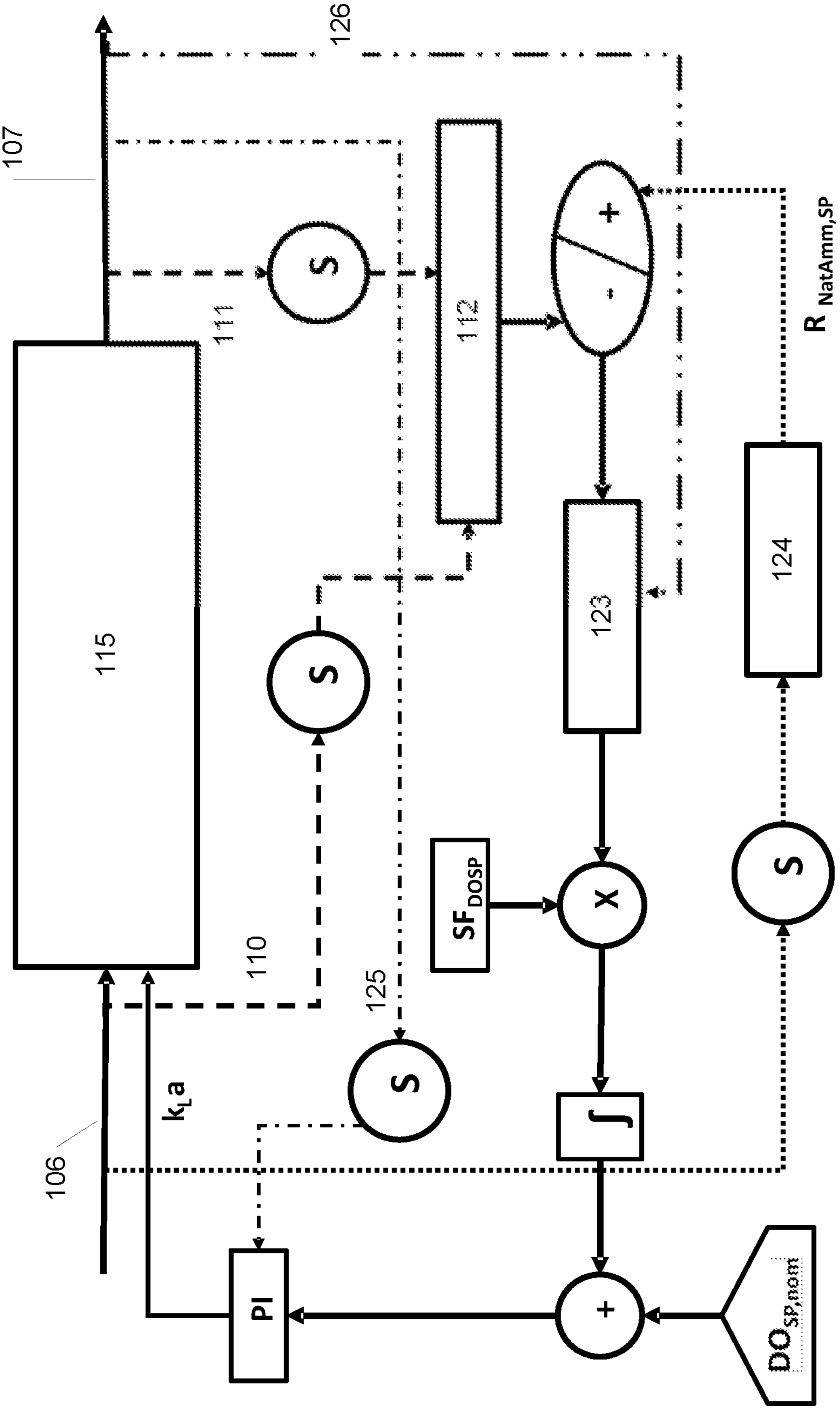
126
107
111
112
115
110
125
106
123
124
S
+
-
X
∫
PI
SF DOSP
DO SP,nom
R NatAmm,SP
kLa

Fig. 6

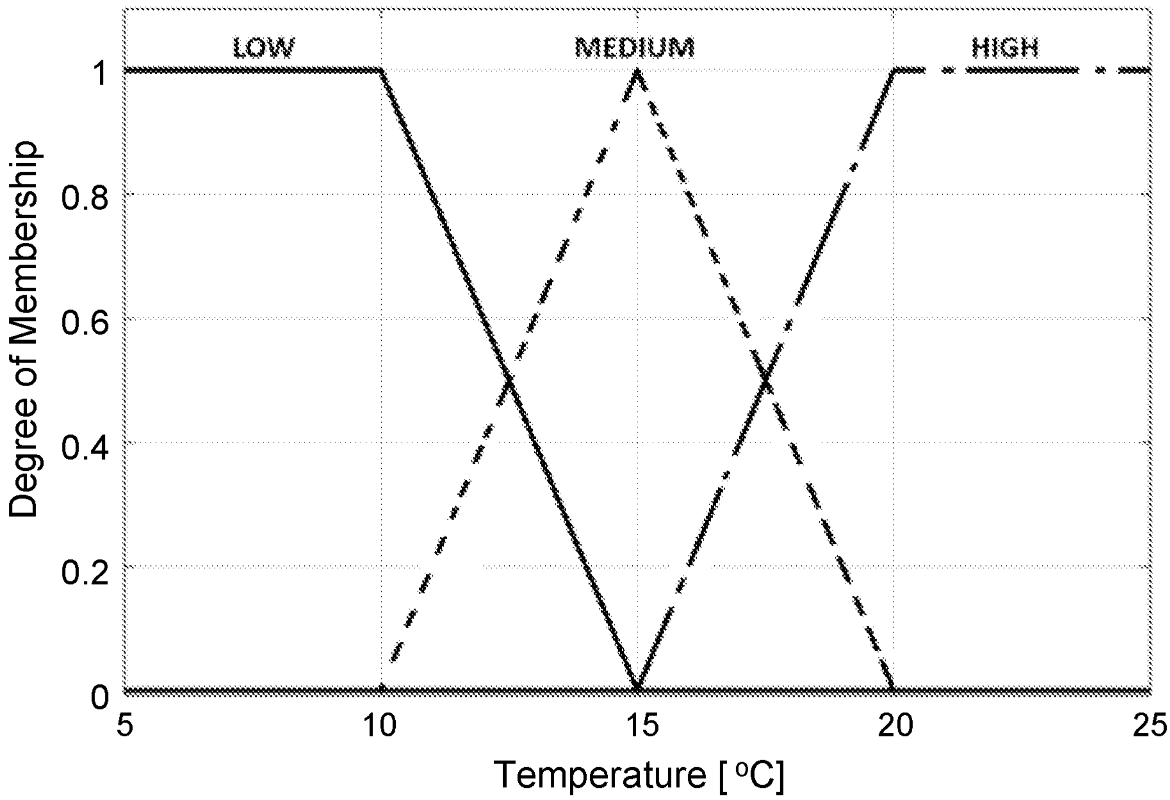
LOW
MEDIUM
HIGH
Degree of Membership
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
Temperature [oC]

Fig. 7a

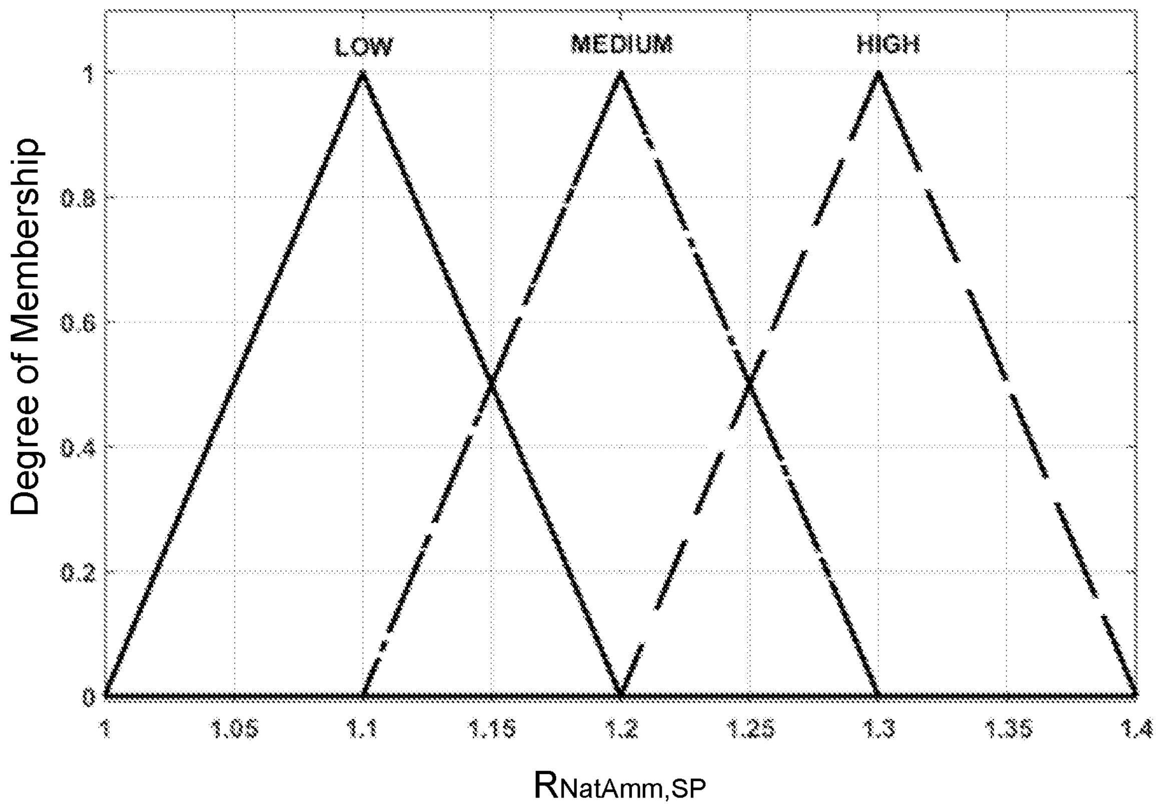
LOW
MEDIUM
HIGH
Degree of Membership
1
0.8
0.6
0.4
0.2
0
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
RNatAmm,SP

Fig. 7b

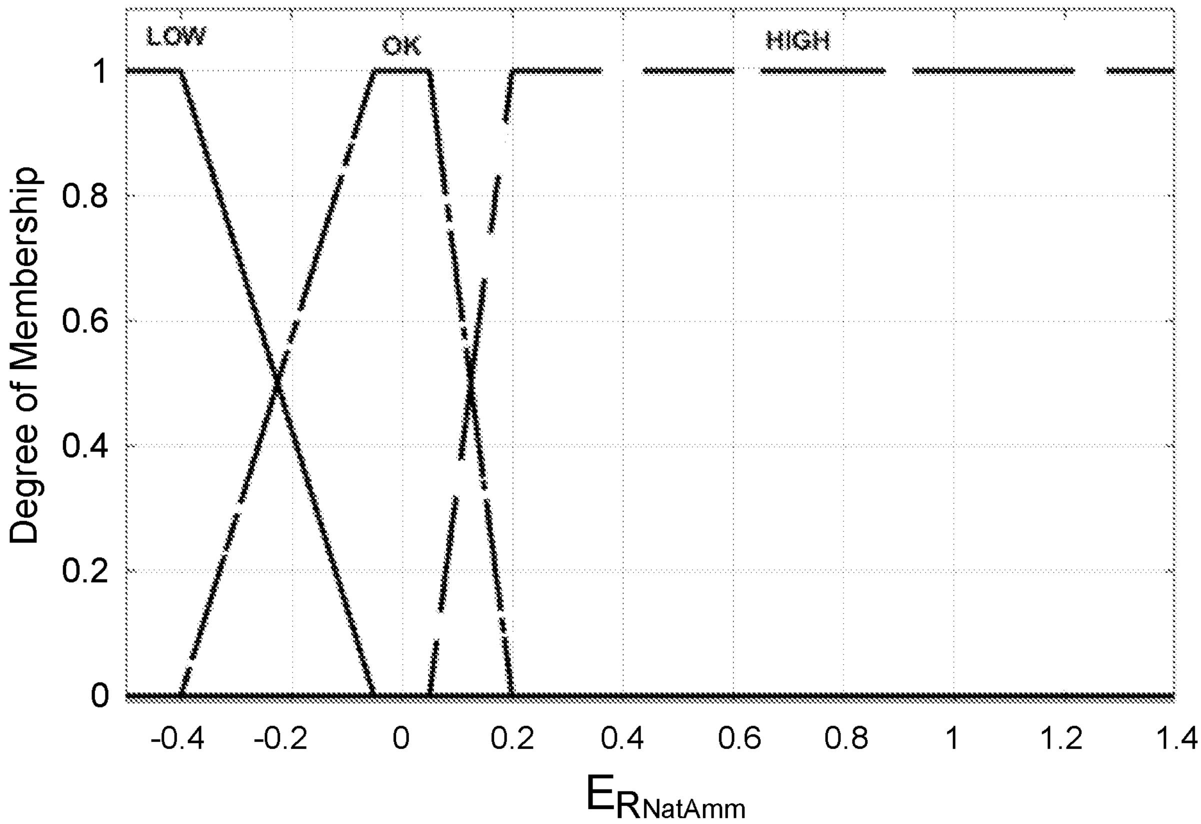
LOW
OK
HIGH
Degree of Membership
1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$E_{R_{NatAmm}}$

Fig. 8a

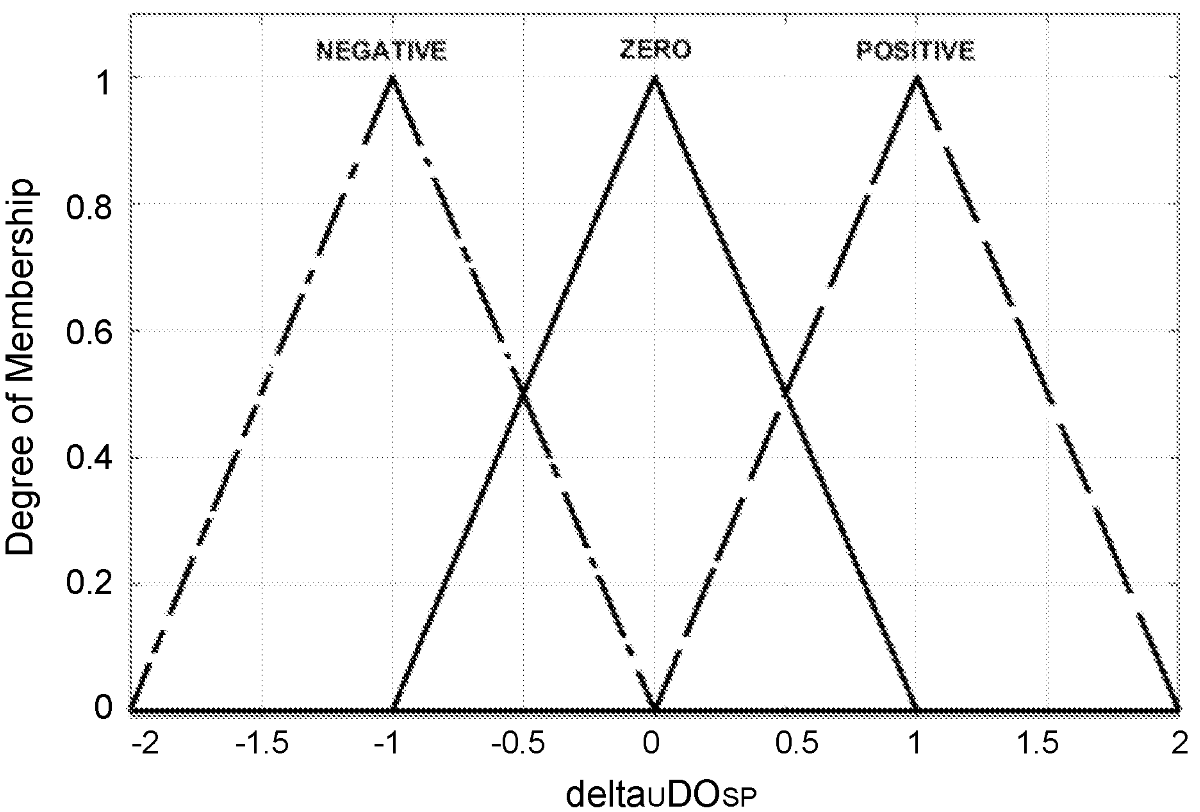
NEGATIVE
ZERO
POSITIVE
Degree of Membership
1
0.8
0.6
0.4
0.2
0
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
$deltauDO_{SP}$

Fig. 8b

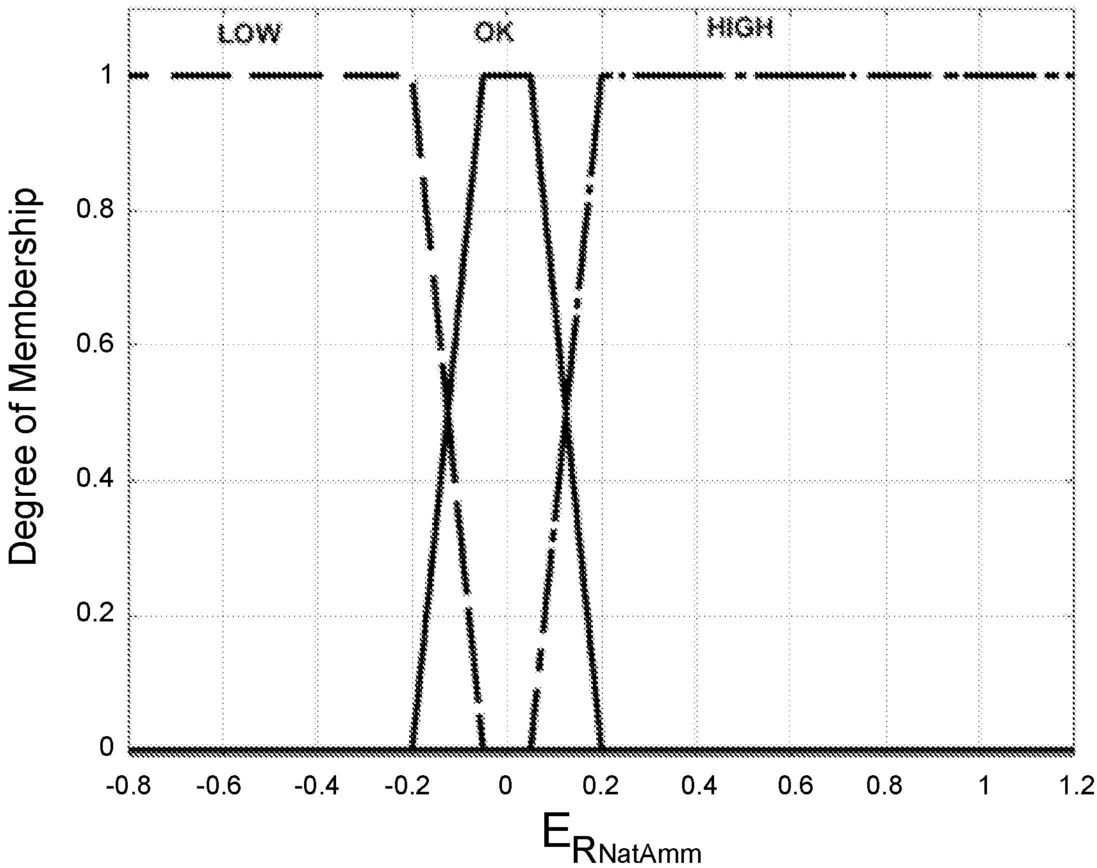
LOW
OK
HIGH
1
0.8
0.6
0.4
0.2
0
Degree of Membership
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
$E_{R_{NatAmm}}$

Fig. 8c

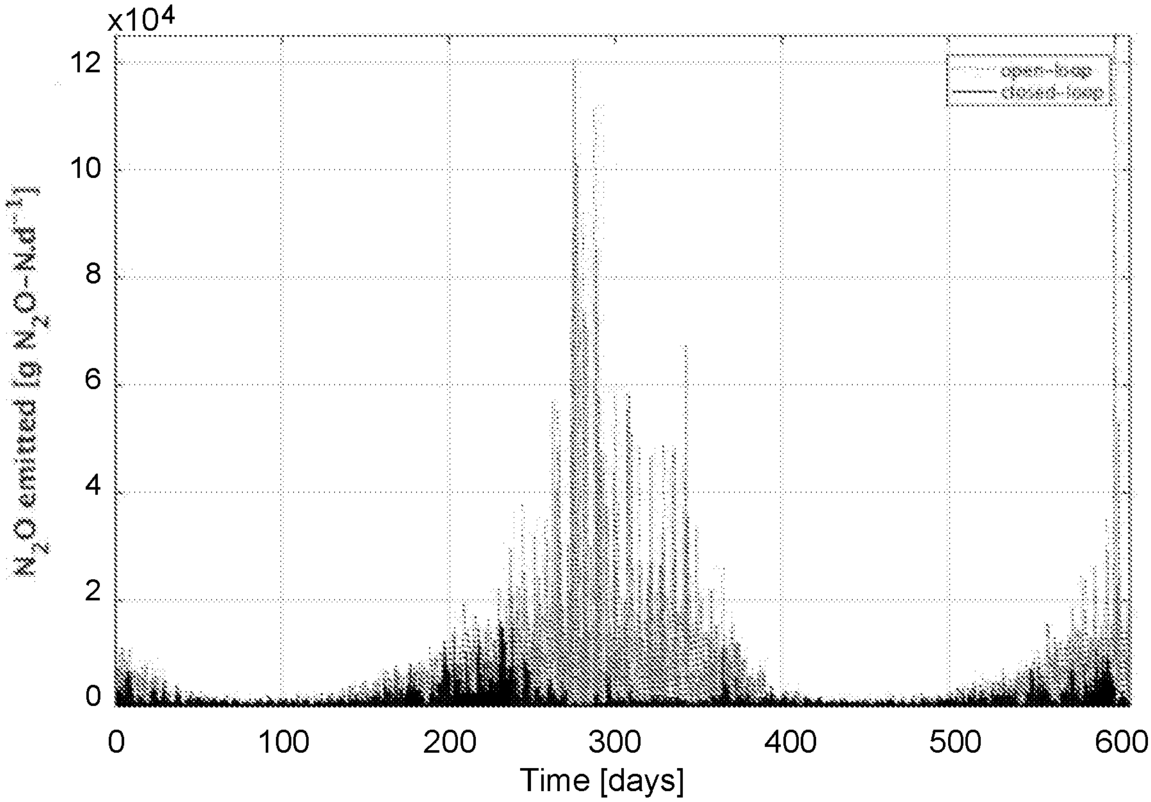
x10⁴
12
10
8
6
4
2
0
N_2O emitted [g N_2O-N.d^{-1}]
open-loop
closed-loop
0
100
200
300
400
500
600
Time [days]

Fig. 9a

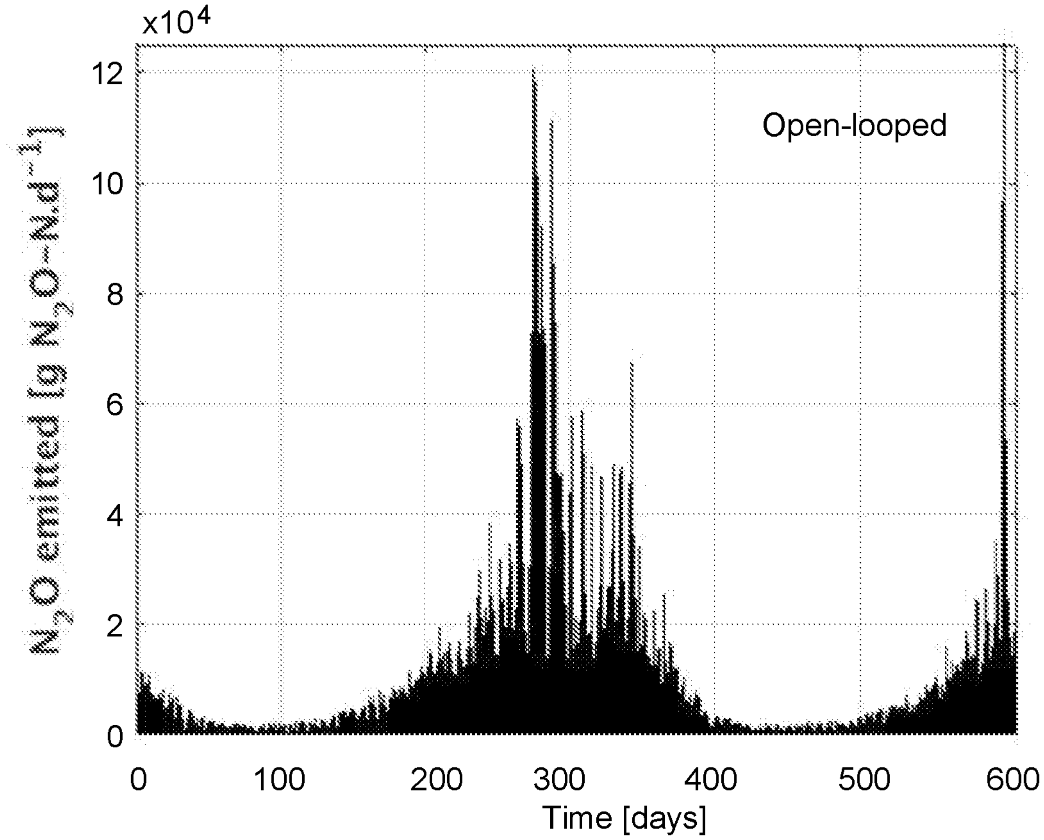
x10^4
12
10
8
6
4
2
0
N2O emitted [g N2O-N.d-1]
Open-looped
0
100
200
300
400
500
600
Time [days]

Fig. 9b

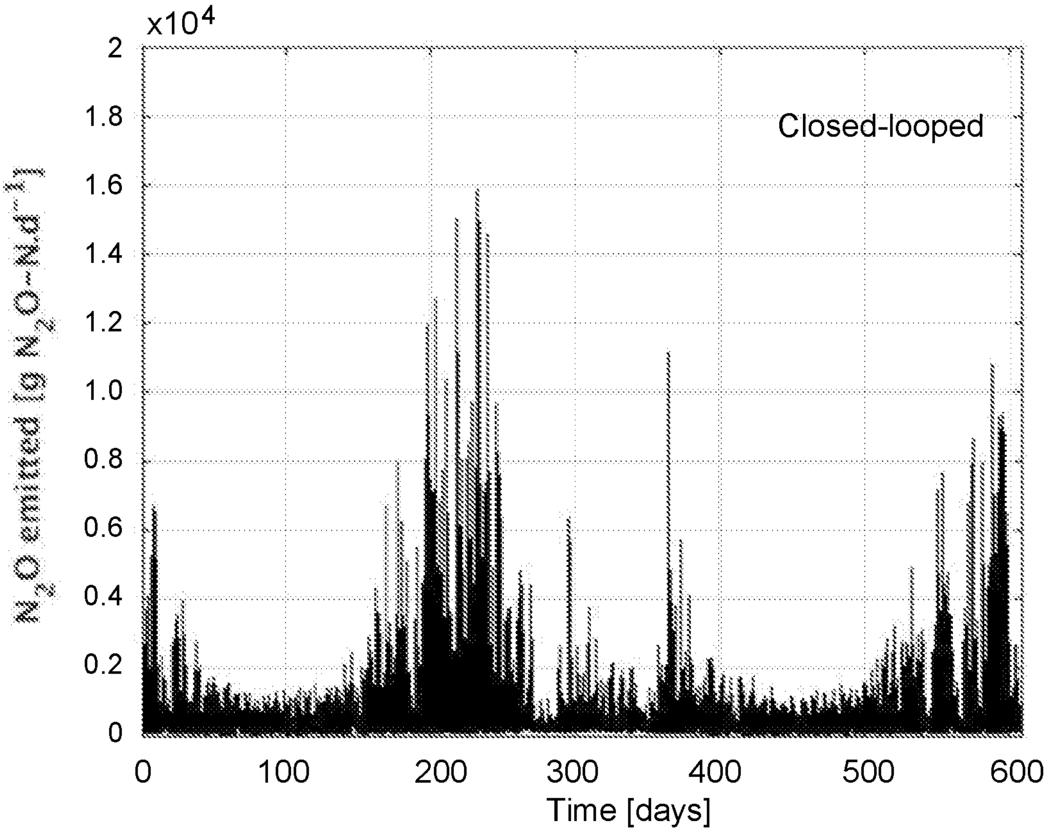
x10^4
2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
N2O emitted [g N2O-N.d-1]
Closed-looped
0
100
200
300
400
500
600
Time [days]

Fig. 9c

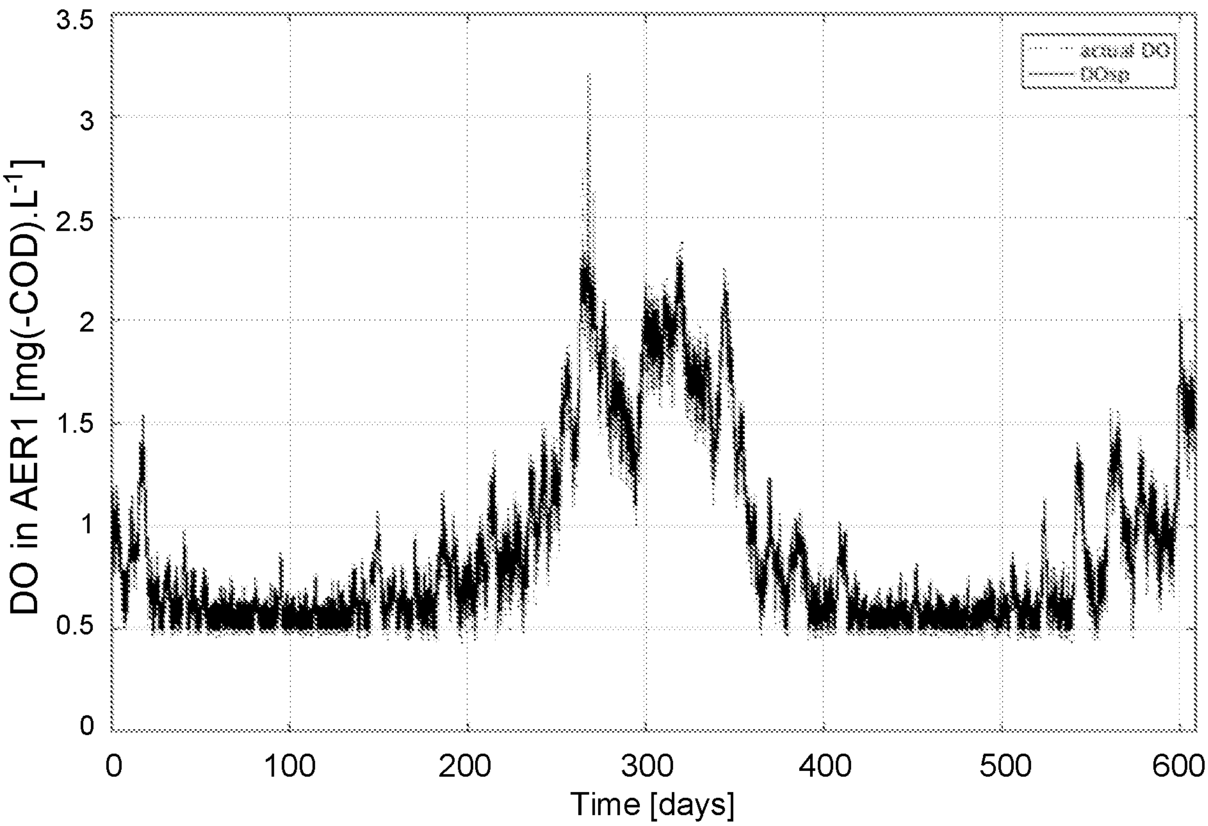
3.5
3
2.5
2
1.5
1
0.5
0
DO in AER1 [mg(-COD).L-1]
0
100
200
300
400
500
600
Time [days]
actual DO
DOsp

Fig. 9d

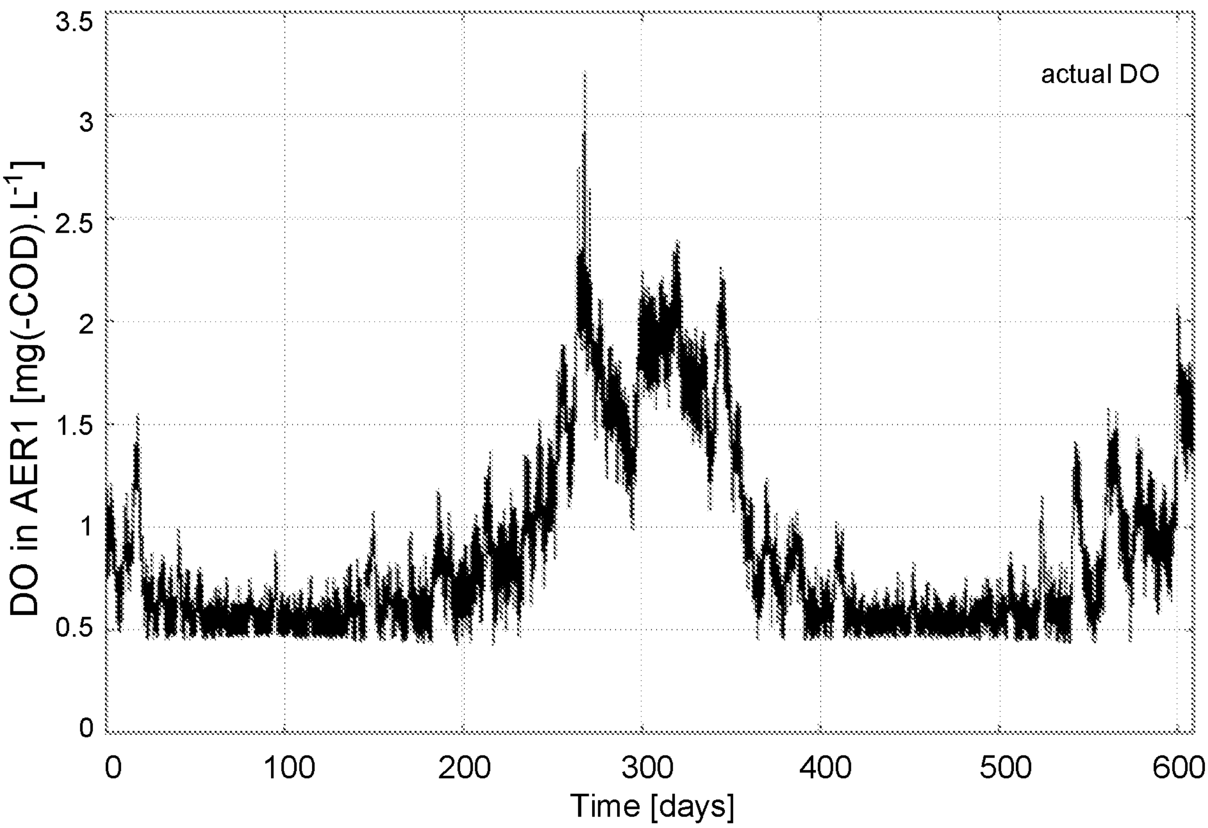
3.5
3
2.5
2
1.5
1
0.5
0
DO in AER1 [mg(-COD).L-1]
0
100
200
300
400
500
600
Time [days]
actual DO

Fig. 9e

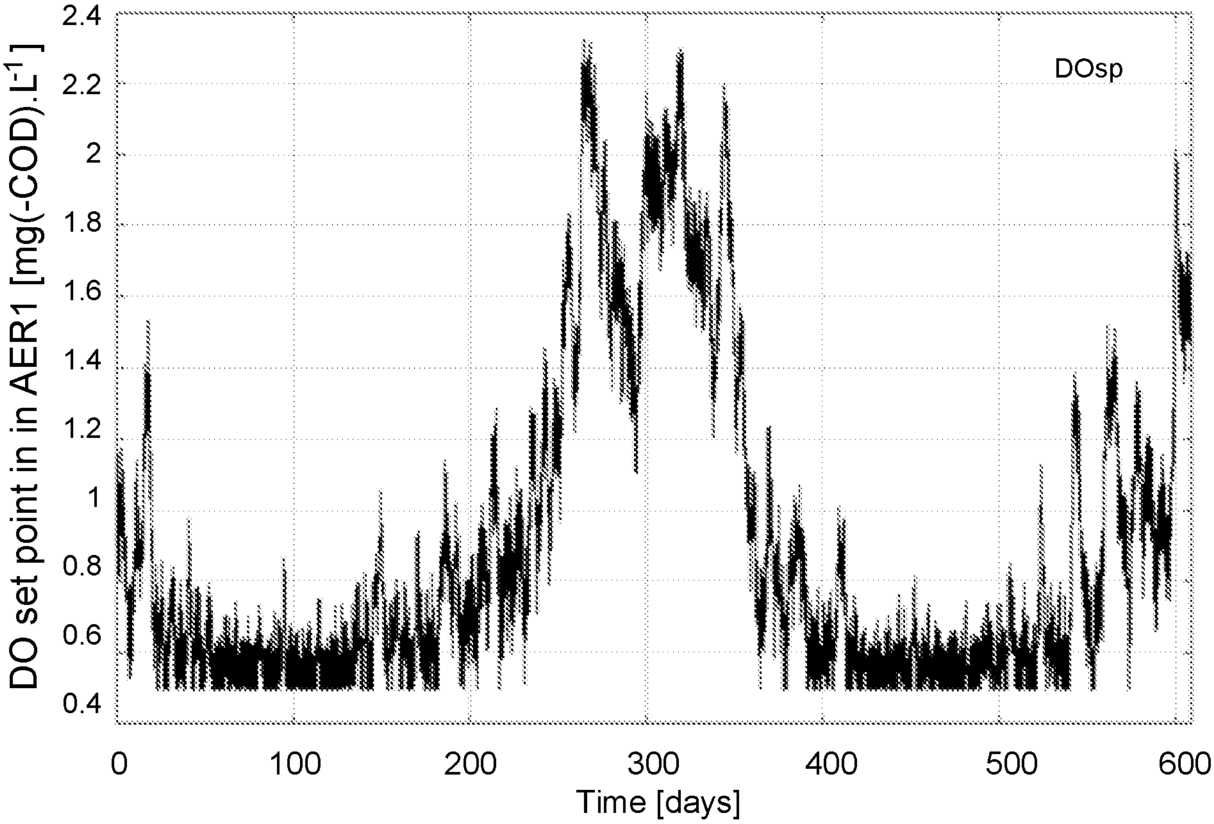
DOsp
DO set point in in AER1 [mg(-COD).L-1]
Time [days]
0
100
200
300
400
500
600
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4

Fig. 9f

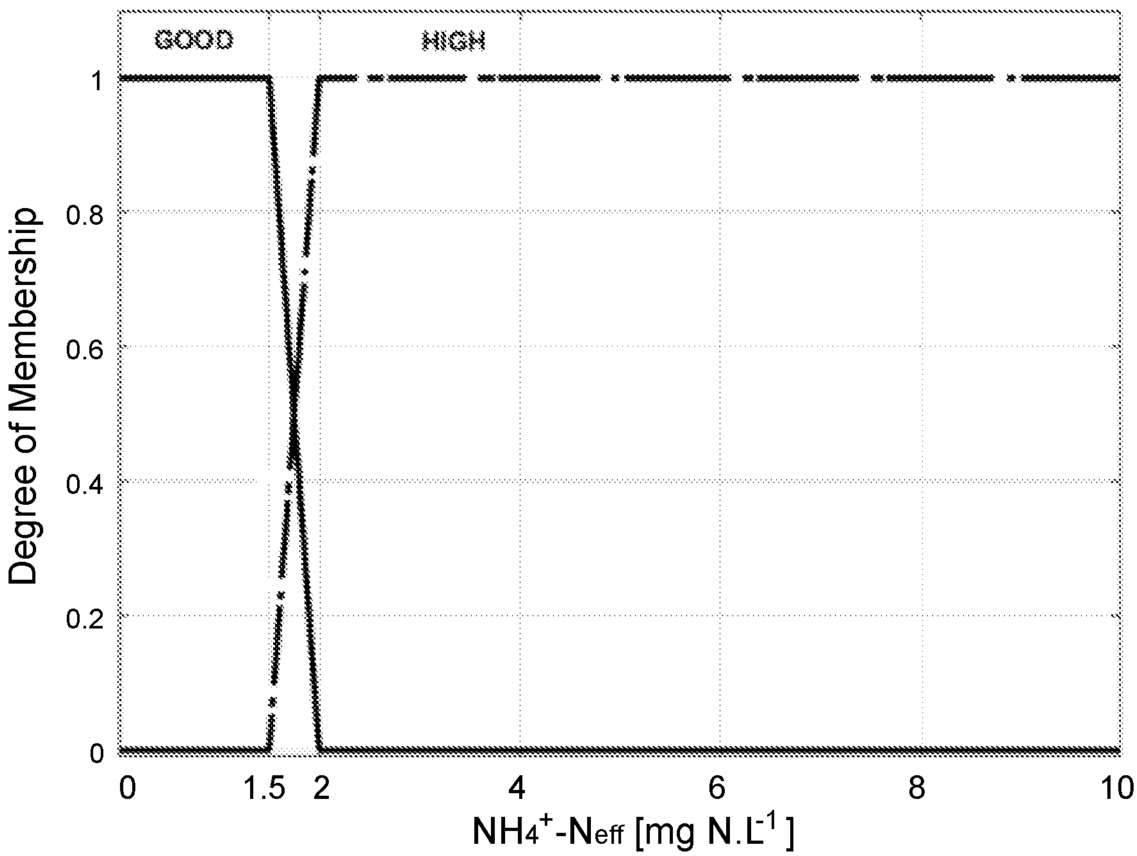
GOOD
HIGH
Degree of Membership
NH4+-Neff [mg N.L-1]
0
1.5
2
4
6
8
10
1
0.8
0.6
0.4
0.2
0

Fig. 11

	N_2O e.f. 1 [% g N_2O-N.g^{-1} TKN_{in}]			N_2O e.f. 2 [% g N_2O-N.g^{-1} TKN_{rem}]		
MODEL→	A	B	C	A	B	C
Open-loop	0.418	0.048	0.39	0.444	0.052	0.41
Regulatory	0.0566	0.0248	0.067	0.068	0.026	0.069
Cascade	0.045	0.0208	0.047	0.047	0.0217	0.048
Sens and act	0.047	0.0226	0.049	0.049	0.0234	0.051

	η_{TN} [% g TN_{rem}·g^{-1} TN_{in}]			η_{TKN} [% g TKN_{rem}·g^{-1} TKN_{in}]			AEC [kWh.d^{-1}]		
MODEL→	A	B	C	A	B	C	A	B	C
Open-loop	74.22	68.22	79.9	94.25	91.72	94.8	4193.1	4193.1	4193.1
Regulatory	67.3	67	74.3	96.3	95.7	96.8	3276.7	3194.62	3209.5
Cascade	66.76	66.73	73.63	66.76	66.73	73.63	3133.6	3068.3	3167.4
Sens and act	66.64	66.88	74.4	66.64	66.88	74.4	3172.6	3129.95	3134.7

Fig. 10

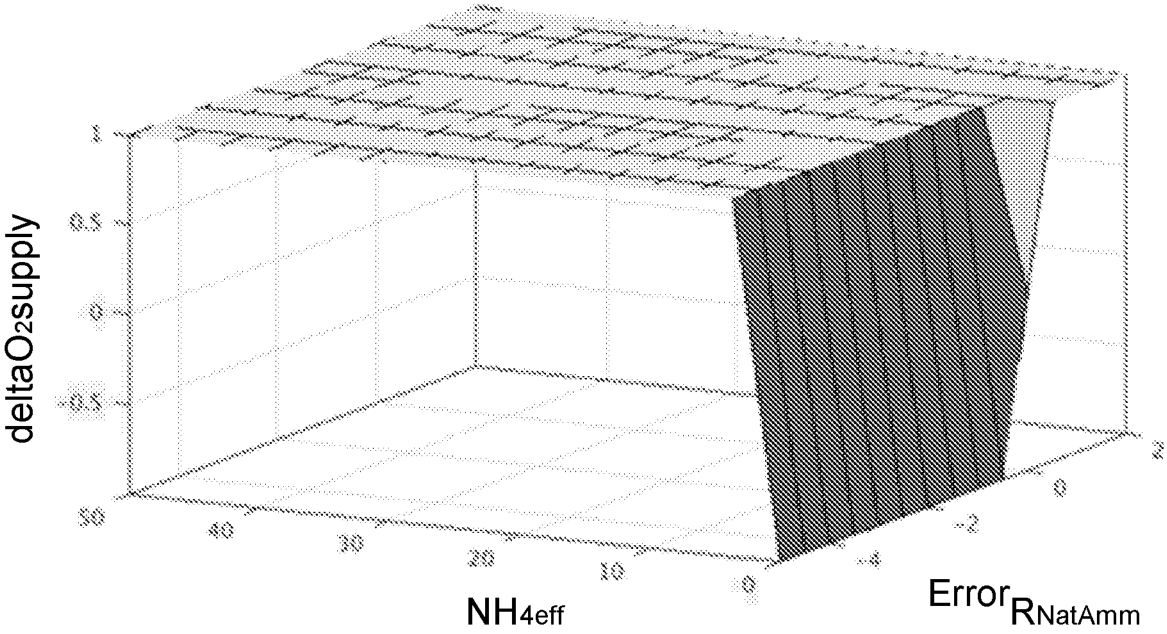

Fig. 12a

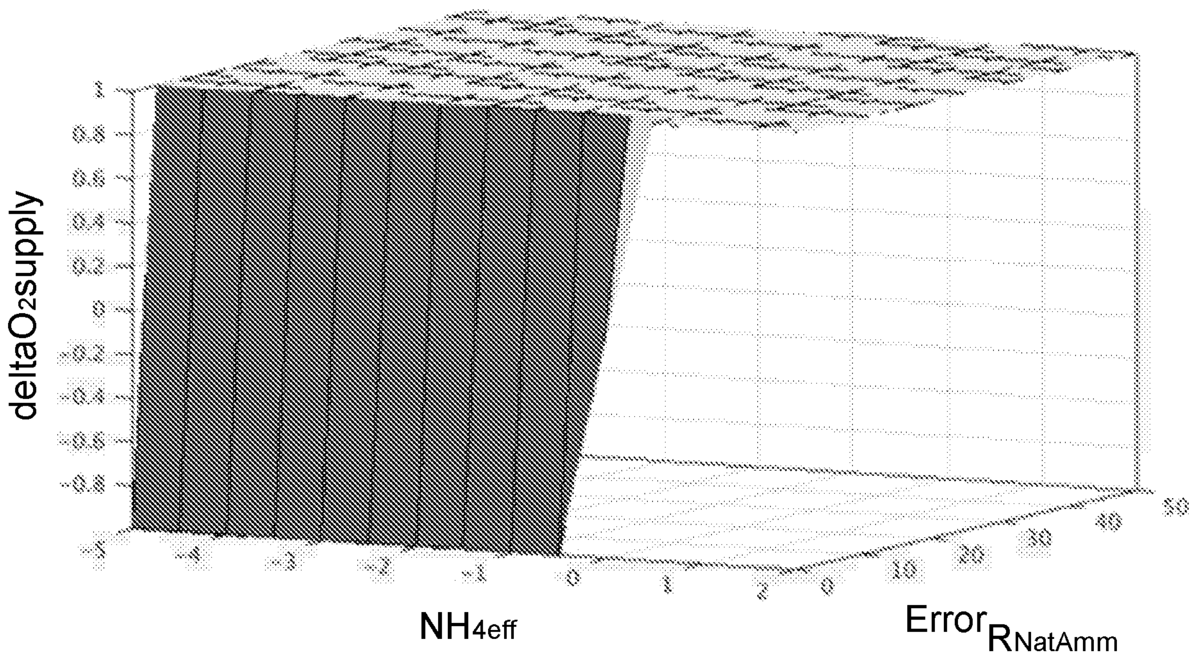

Fig. 12b

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2017/050186

A. CLASSIFICATION OF SUBJECT MATTER
INV. C02F3/00 C02F3/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013/256217 A1 (LEMAIRE ROMAIN [FR] ET AL) 3 October 2013 (2013-10-03) figure 4 paragraph [0035] paragraphs [0114] - [0121] paragraphs [0146] - [0149] paragraphs [0180] - [0197] paragraph [0229] -----	1-20
X	US 2014/263041 A1 (REGMI PUSKER [US] ET AL) 18 September 2014 (2014-09-18) claims 7, 11 ----- -/--	1-20

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
13 July 2017	31/07/2017

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